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# Study of the Nature of Ozone, Oxides of Nitrogen, and Nonmethane Hydrocarbons in Tulsa, Oklahoma. Volume III
## Data Analysis and Interpretation

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Prepared for

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16. ABSTRACT

The 1977 Tulsa Study was conducted to provide the EPA with a high quality data base for use in testing various photochemical simulation models. The city of Tulsa represents an isolated urban area, and thus provides an excellent location to observe ozone formation from an individual urban area. The monitoring program was designed to facilitate the observation of incoming pollutant transport and the formation of ozone downwind. Pollutant and meteorological measurements were made from ground level monitoring sites and aboard an instrumented aircraft.

This volume reports on the analysis and interpretation of measured parameters. Included are analyses of (1) the meteorological representativeness of the study area, (2) the statistical relationship of ozone to other parameters, (3) the hydrocarbon and aircraft ozone measurements, and (4) case studies of periods of high ozone concentrations.

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## Volume III
## Data Analysis and Interpretation

by

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Research Triangle Park, N.C. 27709

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# 1.0 INTRODUCTION

## 1.1 BACKGROUND

Anthropogenic emissions of nonmethane hydrocarbons (NMHC) and oxides of nitrogen ($NO_x$) in the presence of strong solar radiation are involved in a complex sequence of chemical reactions that result in the formation of ozone. Local meteorological processes such as the diurnal variation of solar radiation, temperature, and mixing height, as well as the local wind speed and direction, influence the production and distribution of ozone near an urban source area. In addition, synoptic-scale meteorological conditions can lead to transport of ozone over large distances and can contribute to a higher background ozone concentration.

The highly nonlinear relationships between maximum ozone concentration and initial concentrations of ozone precursors (NMHC and $NO_x$) have been demonstrated in smog chamber experiments. This nonlinearity and the large-scale transport of ozone add to the complexity of developing ozone control strategies to achieve the ozone National Ambient Air Quality Standard (NAAQS). The NAAQS for ozone at the time of this study was a maximum 1-hour concentration of 0.08 ppm, not to be exceeded more than once per year. In 1979 the NAAQS was revised to permit a maximum ozone concentration of 0.12 ppm, not to be exceeded more than once per year.

Prior control strategies to meet the NAAQS for ozone involve reducing emissions of NMHC according to guidelines outlined in Appendix J, Part 51, Title 40 of the Code of Federal Regulations. The applicability of the Appendix J approach for all urban areas has been questioned and alternate methodologies based on photochemical simulation models are being tested. One such procedure, known as the Empirical Kinetic Modeling Approach, is now under consideration. This method is described in an EPA document entitled Uses, Limitations and Technical Basis of Procedures for Quantifying Relationships between Photochemical Oxidants and Precursors.(1) The validation of such models requires extensive amounts of ambient air quality data. Another, more complex model is the SAI (Systems Applications Inc.) photochemical model which computes hourly ozone concentrations across a grid based upon inputs of precursor emissions, meteorological conditions and air quality boundary conditions.

## 1.2 RESEARCH OBJECTIVES

### 1.2.1 Objectives of the Field Measurements Program

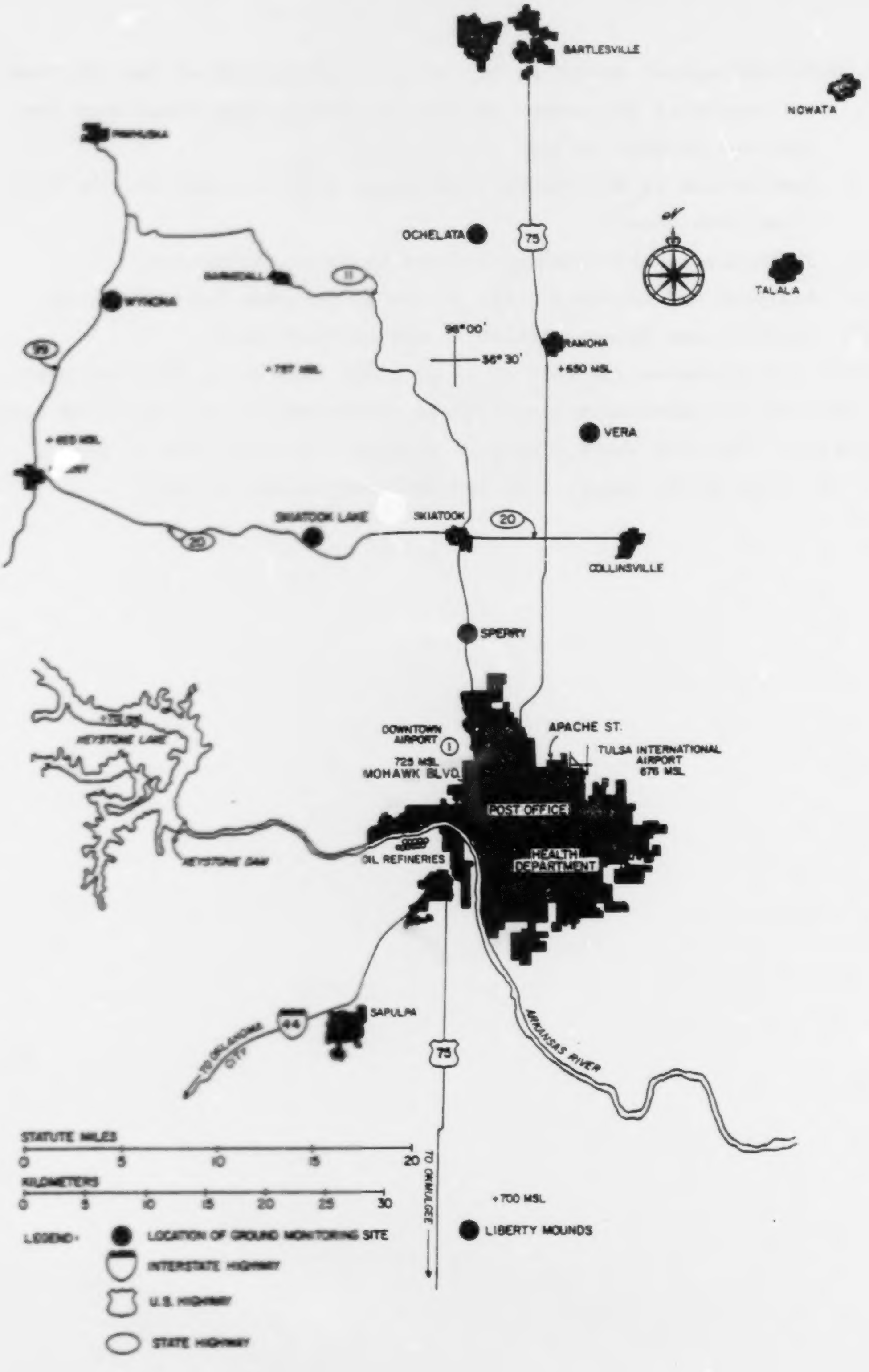
The principal objective of the field measurements program was to provide EPA with a high quality data base to be used in testing various photochemical simulation models. The city of Tulsa represents an isolated urban area, and thus provides an excellent location to observe ozone formation from an individual urban area. The large urban areas nearest to Tulsa are Oklahoma City, approximately 160 km (100 mi) to the southwest, and Dallas-Fort Worth, Texas, approximately 350 km (220 mi) to the south. The eight stations comprising the surface monitoring network were located to facilitate the observation of incoming pollutant transport and the formation of ozone downwind. The location of the eight surface stations are shown in Figure 1.1 on a map of the Tulsa area. Upwind and downwind measurements were also obtained aboard an instrumented aircraft during part of the study.

### 1.2.2 Objectives of the Data Analysis and Interpretation Effort

The principal objectives of the data analysis and interpretation effort, presented in this volume, were to: (a) determine the concentrations of ozone and precursors transported into the Tulsa area; (b) determine the net production of ozone downwind of Tulsa as a result of urban emissions in Tulsa; (c) provide insight into the causes of high ozone concentrations (>0.10 ppm) measured downwind of Tulsa; (d) determine the distance downwind of Tulsa that maximum ozone concentrations typically occur; (e) investigate the relative contributions of various source categories to the nonmethane hydrocarbon concentrations measured in and around Tulsa; and (f) conduct intensive analyses of selected case study days to relate observed pollutant concentrations to precursor sources and observed meteorological conditions, and to provide support for EPA modeling and control strategy efforts.

## 1.3 ANALYSIS APPROACH AND REPORT ORGANIZATION

This report includes three major sections. Section 2.0 lists the major conclusions drawn from the analysis and interpretation effort. Section 3.0 presents an analysis of the overall data base and includes the following sections describing the approaches taken to satisfy the objectives of the analysis: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VERA
SKIATOOK LAKE
SKIATOOK
20
20
COLLINSVILLE
SPERRY
KEYSTONE LAKE
KEYSTONE DAM
DOWNTOWN AIRPORT
725 MSL
MOHAWK BLVD.
APACHE ST.
TULSA INTERNATIONAL AIRPORT
676 MSL
POST OFFICE
HEALTH DEPARTMENT
OIL REFINERIES
SAPULPA
44
TO OKLAHOMA CITY
75
ARKANSAS RIVER
STATUTE MILES
0
5
10
15
20
KILOMETERS
0
5
10
15
20
25
30
TO OKMULGEE
+ 700 MSL
LIBERTY MOUNDS
LEGEND:
LOCATION OF GROUND MONITORING SITE
INTERSTATE HIGHWAY
U.S. HIGHWAY
STATE HIGHWAY

Figure 1.1. Map of Tulsa, Oklahoma, and vicinity; locations of ground monitoring sites.

3.1 Meteorological Analysis, including an evaluation of the representativeness of the summer of 1977 to average conditions over the previous 30-year period;

3.2 Examination of Mean Monthly Pollutant Distributions and the Stratified Data Base;

3.3 Statistical Relationship of Ozone to Other Parameters;

3.4 Analysis and Interpretation of the Hydrocarbon Data Base; and

3.5 Analysis and Interpretation of the Aircraft Data.

In Section 4.0 extensive analyses of 14 specific case study days are presented that relate observed meteorological conditions to the resulting ozone distribution. The case study days were grouped into four sets of days: July 21-25, July 28-30, August 2-5, and September 2 and 3, 1977.

## 2.0 PRINCIPAL FINDINGS AND CONCLUSIONS

The principal findings of the data base collected in Tulsa during the summer of 1977, and the conclusions drawn from the data analysis and interpretation effort are summarized below.

1. The average ozone concentrations measured at Liberty Mounds during hours 1000 and 1100 CST, of 0.058 ppm in July, 0.061 ppm in August, and 0.046 ppm in September are assumed to represent the mean background ozone concentrations in the Tulsa area. The ozone that resulted in those concentrations was mixed to the surface from above the height of the nocturnal inversion. Those concentrations are in good agreement with the mean concentrations (ranging from 0.049 to 0.078 ppm) measured above the nocturnal inversion at 2,500 ft MSL by the aircraft on the morning flights at approximately 0630 CST.
2. The concentrations of $NO_x$ measured aboard the aircraft on the morning flights were near the minimum detectable limit of the instrument, implying that very little $NO_x$ was transported to the Tulsa area. The $NO_x$ concentrations at the Liberty Mounds site rarely exceeded 0.010 ppm throughout the study period, further suggesting that very little $NO_x$ was transported to Tulsa.
3. The average concentrations of NMHC and $NO_x$ measured during the 0500 to 0800 CST collection period at the Post Office site, located in the downtown urban area, were 0.534 ppmC and 0.065 ppm, respectively. At the Health Department station, which is located in a residential area of Tulsa, the mean concentrations of NMHC and $NO_x$ during the same 3-hour measurement period were 0.317 ppmC and 0.027 ppm, respectively.
4. Using a technique developed by Kopczynski(1) that relates the acetylene/NMHC ratio to the percentage of the total NMHC due to tailpipe emissions, an estimate of the average contribution from vehicular sources to the NMHC concentrations was found to be 17 percent at Liberty Mounds, 64 percent at the Post Office, and 60 percent at the Health Department.

5. The level of vehicular traffic (as indicated by acetylene), and thus the level of vehicular tailpipe emissions, showed a strong weekday/weekend variation in the city and no pattern of variation at the southern (generally upwind) site, Liberty Mounds.
6. Downwind transport of urban emissions was evidenced by increased amounts of acetylene measured in samples collected downwind of Tulsa between 1300 and 1600 CST, as compared to samples collected between 0800 and 1100 CST. This effect was most noticeable at the Sperry site, 16 km north of the central business district of Tulsa.
7. The mean concentration of $NO_x$ measured at Liberty Mounds between 0500 and 0800 CST was 0.007 ppm. This suggests that urban emissions contributed, on the average, 0.058 and 0.020 ppm of $NO_x$ at the Post Office and Health Department sites, respectively.
8. Following the 0500 to 0800 CST period the concentrations of NO measured at the Health Department were generally near the minimum detectable limit of the instrument. During the afternoon traffic period the concentration of $NO_2$ often increased. At the Post Office the concentration of NO and $NO_2$ often remained high relative to the Health Department throughout the day. This suggests that both industrial and traffic-related sources of $NO_x$ were of a more continuous nature near the central business district Post Office site than they were near the Health Department site.
9. On days when the Post Office site and the Tulsa Downtown Airport were downwind of the petrochemical complex, higher than average concentrations and percentages of low molecular weight alkane species were generally measured during the 0500 to 0800 CST collection period at the Post Office and during low approach morning flights by the aircraft approximately 50 ft above the Downtown Airport runway. This implies that the petrochemical complex had a high rate of emissions of low molecular weight alkanes.
10. The mean $NMHC/NO_x$ ratios during the 0500 to 0800 CST period averaged over the study were 10.9/1 at the Post Office, 14.4/1 at the Health Department, and 45.6/1 at Liberty Mounds. The ratios from

the urban sites were similar to ratios obtained in Los Angeles (10.2/1), St. Louis (8.5/1), and El Paso (14.0/1).(2) The NMHC/$NO_x$ ratio at Liberty Mounds was similar to the ratios obtained at two predominantly rural sites in Ohio of 53.0/1 at McConnelsville and 42.0/1 at Wooster.(3)

11. The concentrations of the naturally occurring hydrocarbons, α-pinene, β-pinene, and isoprene, were quite low (usually less than 5 ppbC for the sum of these three compounds and the known interferents p-xylene and trans-2-pentene).
12. The results of air parcel trajectory analyses investigated for many of the 14 case study days suggested that the air that produced the maximum ozone concentrations in the network typically had been over Tulsa between 1000 and 1200 CST rather than 0500-0800. There was no significant correlation between the maximum ozone concentrations measured at any of the typically downwind sites and the 0500 to 0800 CST NMHC concentrations measured at either of the two urban sites.
13. The data from each station were stratified into urban-influenced (i.e., airflow from Tulsa towards the monitoring site) or nonurban-influenced categories during the photochemically active portion of the day. When the northern stations were classified as nonurban-influenced, the meteorological conditions important for ozone formation, percent sunshine, solar radiation, and temperature were often significantly lower than on days of urban influence and the average ozone concentrations were also lower. The lower ozone concentrations seem to result from the lack of Tulsa emissions rather than the lack of sunshine.
14. The very low concentrations of ozone precursors measured at Liberty Mounds suggest that very little ozone synthesis was possible at that location. The available data both from the surface and the aircraft do not provide any strong evidence of direct ozone transport to Liberty Mounds from any urban area other than Tulsa. On urban-influenced days high ozone concentrations (>0.10 ppm) occurred at Liberty Mounds; on the remaining days, however, the

ozone synthesis was limited at Liberty Mounds. The ozone increase measured at Liberty Mounds on most days with southerly winds was likely due to mixing of ozone from above the height of the nocturnal inversion during the midmorning hours.

15. The ozone precursor concentrations measured during the morning hours at the northern (downwind) sites were generally very low compared to those measured in the city. Therefore, ozone synthesis from local sources at the individual sites most likely represents only a small contribution to the maximum ozone concentrations measured at those sites.

16. As measured at 770 m (2,500 ft) MSL, the net ozone formation due to Tulsa emissions was determined by subtracting the mean background ozone concentration measured on that portion of the horizontal traverses of each afternoon flight that was not obviously in the Tulsa urban plume from the maximum ozone concentration measured during the afternoon horizontal flights. The net ozone formation determined from the data of the aircraft flights that had distinct ozone plumes varied from 0.017 ppm (August 26) to 0.116 ppm (September 3).

17. During the study, Sperry, Vera, and Ochelata were all considered to be simultaneously under urban influence on 39 days. The maximum ozone concentration in the network was measured at Vera (34 km downwind) on 49 percent of those days; at Ochelata (48 km downwind) on 32 percent of those days, and at Sperry (14 km downwind) on only 8 percent of those days.

18. On 3 of the 4 days that the aircraft measured a distinct ozone plume, the maximum ozone concentration was measured approximately 48 km (30 mi) north of the center of Tulsa. On the remaining day, the maximum ozone concentration was measured approximately 32 km (20 mi) downwind.

# 3.0 DATA ANALYSIS AND INTERPRETATION

## 3.1 METEOROLOGICAL ANALYSIS

### 3.1.1 Meteorological Representativeness of Tulsa, Summer 1977

In order to assess the climatological normalcy of the summer of 1977 (July, August, and September) in Tulsa, Oklahoma, to insure that the meteorological conditions were not greatly different from previous summers, a number of meteorological parameters were examined including temperature, relative humidity, cloud cover, winds, and high-pressure systems. The data for this investigation were obtained from the NOAA publications Climatological Data, National Summary, and Local Climatological Data (LCD) monthly and annual summaries for the National Weather Service Office at Tulsa International Airport. Unless otherwise indicated, "normal" refers to the 30-year period from 1941 through 1970. When data were available, a 10-year average (1968 through 1977) was also determined. Later, the summer of 1977 is compared climatologically with the summers of 1974, 1975, and 1976, specifically because of the large amount of reliable ozone data available for those four years.

#### 3.1.1.1 Temperature--

In 1977 the mean daily temperature for each month was above the normal, but was within one standard deviation of the 10-year and normal mean (Table 3.1). The third warmest July and August and the warmest September of the past 10 years were recorded in 1977.

Examination of the average maximum and minimum temperature (Table 3.2) suggests that the above-average mean temperatures were due to higher minimum temperatures rather than higher maximum temperatures.

TABLE 3.1. AVERAGE DAILY TEMPERATURE

| Month | Means | | | Standard Deviation | | 1977 |
|---|---|---|---|---|---|---|
| | 71 Yr | Normal | 10 Yr | Normal | 10 Yr | |
| Jul | 82.5 | 82.1 | 82.4 | 3.2 | 2.2 | 84.8 |
| Aug | 81.8 | 81.4 | 80.8 | 3.0 | 1.9 | 81.7 |
| Sep | 74.0 | 73.3 | 72.4 | 2.8 | 3.4 | 75.6 |

TABLE 3.2. AVERAGE MAXIMUM AND MINIMUM TEMPERATURES (°F)

| Month | Maximum |  |  | Minimum |  |  |
|---|---|---|---|---|---|---|
|  | Normal | 10-Yr Average | 1977 | Normal | 10-Yr Average | 1977 |
| Jul | 92.8 | 93.2 | 95.2 | 71.4 | 71.5 | 74.3 |
| Aug | 92.7 | 91.9 | 91.4 | 70.0 | 69.7 | 72.0 |
| Sep | 84.8 | 82.8 | 84.8 | 61.7 | 62.0 | 66.4 |

TABLE 3.3. DAYS WITH EXTREME TEMPERATURES

| Month | Temp >90° F |  |  | Temp >100° F |  |  |
|---|---|---|---|---|---|---|
|  | Normal | 10-Yr Average | 1977 | Normal | 10-Yr Average | 1977 |
| Jul | 23 | 24 | 26 | <1 | 4 | 4 |
| Aug | 21 | 22 | 21 | <1 | 4 | 4 |
| Sep | 8 | 8 | 9 | <1 | 0 | 0 |

### 3.1.1.2 Relative Humidity--

Relative humidity for the summer of 1977 was compared to the normal for four different times of the day: 0000, 0600, 1200, and 1800 CST (Table 3.4). July was found to be normal with respect to relative humidity; however, August and September were more humid, particularly at noon and 1800. Because temperatures were above normal, the higher relative humidities of August and September indicate more moisture than usual in the air.

TABLE 3.4. RELATIVE HUMIDITY

| 00 CST | Normal | 1977 | 06 CST | Normal | 1977 |
|---|---|---|---|---|---|
| Jul | 73 | 74 | Jul | 83 | 83 |
| Aug | 74 | 77 | Aug | 85 | 86 |
| Sep | 82 | 85 | Sep | 89 | 91 |
| 12 CST | Normal | 1977 | 18 CST | Normal | 1977 |
| Jul | 54 | 54 | Jul | 50 | 50 |
| Aug | 54 | 61 | Aug | 50 | 57 |
| Sep | 61 | 67 | Sep | 60 | 67 |

TABLE 3.5. PRECIPITATION (INCHES)

| Month | Means |  |  | Standard Deviation |  |  |
|---|---|---|---|---|---|---|
|  | 90 Yr | Normal | 10 Yr | Normal | 10 Yr | 1977 |
| Jul | 3.20 | 3.51 | 2.41 | 3.3 | 1.9 | 2.00 |
| Aug | 3.22 | 2.95 | 3.36 | 1.8 | 1.6 | 4.86 |
| Sep | 3.89 | 4.07 | 6.28 | 2.9 | 5.3 | 5.57 |

3.1.1.3 Precipitation--

Generally speaking, July 1977 was drier than normal; August, wetter than normal; and September had about normal rainfall (Table 3.5).

With the exception of August, precipitation for all 3 months fell within one standard deviation of the mean for both the normal period of record (1941-1970) and the previous 10 years (1968-1977). August's rainfall of 4.86 inches was slightly more than one standard deviation above the normal.

There were 2 more days with measureable precipitation in both August and September than is normal for those months (Table 3.6).

3.1.1.4 Clear Days--

Consistent with the temperature and precipitation data already presented, July 1977 had a significantly greater number of clear days than normal--19--and a higher than normal percentage of possible sunshine (Table 3.7). August and September had only 6 clear days and lower than normal percentages of possible sunshine.

TABLE 3.6. DAYS WITH MEASUREABLE PRECIPITATION

| Month | Normal | 10 Yr Average | 1977 |
|---|---|---|---|
| Jul | 7 | 6 | 7 |
| Aug | 7 | 7 | 9 |
| Sep | 8 | 10 | 10 |

TABLE 3.7. CLEAR DAYS AND SUNSHINE

| Month | Clear Days Normal | Clear Days 1977 | Percent Possible Sunshine Normal | Percent Possible Sunshine 1977 |
|---|---|---|---|---|
| Jul | 12 | 19 | 72 | 79 |
| Aug | 13 | 6 | 72 | 64 |
| Sep | 12 | 6 | 65 | 60 |

TABLE 3.8. PREVAILING WIND DIRECTION AND AVERAGE WIND SPEED (mph)

| Month | Normal | 1977 |
|---|---|---|
| Jul | S/9.3 | 170°/9.6 |
| Aug | SSE/9.1 | 170°/10.4 |
| Sep | SSE/9.3 | 150°/9.8 |

TABLE 3.9. ANTICYCLONE FREQUENCY* AND DURATION†

| | Avg. No. | Maximum | Minimum | 1977 |
|---|---|---|---|---|
| Jul | 1.8 (19) | 3 (42) | 0 (6) | 1 (10) |
| Aug | 1.0 (35) | 2 (66) | 0 (12) | 1 (26) |
| Sep | 2.1 (20) | 3 (36) | 1 (6) | 1 (18) |

*Number of anticyclones passing within 500 km.
†Number of hours anticylone center was within 500 km.

### 3.1.1.5 Winds--

During the summer of 1977, the normal south to south-southeasterly flow prevailed and wind speeds for the period were slightly greater than normal, particularly in August (Table 3.8).

### 3.1.1.6 High-Pressure Systems--

The tracks of anticyclones were examined for the 10-year period of 1968-1977. High-pressure systems were catalogued when their centers passed within 500 km of Tulsa. During 1977, only three systems traversed the area during the 3-month period (Table 3.14). Normally, about five high-pressure systems would be expected during this period. Also, the amount of time that the Tulsa area was under the influence of high pressure was significantly below the average, particularly in July and August (Table 3.15).

### 3.1.1.7 Comparing 1977 to the Three Previous Years--

Because ozone data from a fairly dense network are available for the period 1974-1977 for the Tulsa area, certain meteorological parameters were examined in order to identify periods of unusual weather. Table 3.10 shows that warm months during this period include July 1974, July 1977, and September 1977. Cool months include August 1974, September 1974, and September 1975. Examination of average maximum daily temperatures (Table 3.11) and average minimum daily temperatures (Table 3.12) confirms the selection of these months as somewhat unusual with respect to temperature.

Although there was a considerable amount of scatter in the precipitation data (Table 3.13), only three of the months fell outside one standard deviation of the normal: August 1974, September 1974, and August 1977.

TABLE 3.10. DAILY AVERAGE TEMPERATURE

| | Normal | 1974 | 1975 | 1976 | 1977 |
|---|---|---|---|---|---|
| Jul | 82.1 | 85.4 | 81.2 | 81.4 | 84.8 |
| Aug | 81.4 | 78.3 | 82.2 | 79.7 | 81.7 |
| Sep | 73.3 | 64.7 | 69.2 | 72.8 | 75.6 |

TABLE 3.11. AVERAGE MAXIMUM TEMPERATURE

| | Normal | 1974 | 1975 | 1976 | 1977 |
|---|---|---|---|---|---|
| Jul | 92.8 | 97.5 | 91.6 | 92.7 | 95.2 |
| Aug | 92.7 | 88.6 | 93.1 | 91.8 | 91.4 |
| Sep | 84.8 | 74.2 | 80.8 | 84.0 | 84.8 |

TABLE 3.12. AVERAGE MINIMUM TEMPERATURE

| | Normal | 1974 | 1975 | 1976 | 1977 |
|---|---|---|---|---|---|
| Jul | 71.4 | 73.2 | 70.7 | 70.1 | 74.3 |
| Aug | 70.0 | 67.9 | 71.3 | 67.5 | 72.0 |
| Sep | 61.7 | 55.1 | 57.6 | 61.5 | 66.4 |

TABLE 3.13. PRECIPITATION DAYS AND AMOUNTS

| | Normal | 1974 | 1975 | 1976 | 1977 |
|---|---|---|---|---|---|
| Jul | 7 (3.51) | 2 (0.55) | 6 (2.14) | 6 (4.37) | 7 (2.00) |
| Aug | 7 (2.95) | 9 (5.30) | 9 (3.52) | 7 (1.17) | 9 (4.86) |
| Sep | 8 (4.07) | 10 (11.78) | 9 (3.34) | 7 (2.60) | 10 (5.57) |

Each of these months was wetter than normal. Two relatively dry months were July 1974 and August 1976. As for the number of days with measureable precipitation, no great departures from normal are noted except for July 1974 when it rained only 2 days. Even September 1974, with 11.78 inches of total rainfall, had only 10 rain days.

Large deviations from the normal percentage of possible sunshine (Table 3.14) occurred for only 3 months: July 1974 (15 percent above normal), August 1974 (19 percent below normal), and September 1975 (13 percent below normal). Generally, July had above normal percentage of sunshine, while August and September were below normal for the 4-year period.

For the 4-year period, resultant wind directions were within 20° of normal with the exception of September 1974, which had a definite easterly flow as opposed to the prevailing south-southeasterly direction normal for that month (Table 3.15). September 1974 also had abnormally heavy rainfall. Generally, wind speeds fell within 1 mph of the normal monthly average with these exceptions: July 1975 (1.7 mph low), September 1975 (1.1 mph low), September 1976 (1.2 mph low), and August 1977 (1.3 mph high).

TABLE 3.14. PERCENTAGE OF POSSIBLE SUNSHINE

| | Normal | 1974 | 1975 | 1976 | 1977 |
|---|---|---|---|---|---|
| Jul | 72 | 87 | 69 | 79 | 79 |
| Aug | 72 | 53 | 70 | 75 | 64 |
| Sep | 65 | 57 | 52 | 58 | 60 |

TABLE 3.15. RESULTANT WIND DIRECTION/AVERAGE WIND SPEED (mph)

| | Normal | 1974 | 1975 | 1976 | 1977 |
|---|---|---|---|---|---|
| Jul | S/9.3 | 190/9.6 | 190/7.6 | 200/9.4 | 170/9.6 |
| Aug | SSE/9.1 | 170/9.6 | 180/9.4 | 150/9.4 | 170/10.4 |
| Sep | SSE/9.3 | 100/8.5 | 140/8.2 | 150/8.1 | 150/9.8 |

TABLE 3.16. ANTICYCLONE FREQUENCY AND DURATION (hours)

| | 1974 | 1975 | 1976 | 1977 |
|---|---|---|---|---|
| Jul | 2 (24) | 2 (25) | 2 (24) | 1 (10 |
| Aug | 2 (53) | 1 (54) | 0 | 1 (26) |
| Sep | 3 (20) | 3 (18) | 2 (34) | 1 (18) |

Analysis of high-pressure systems passing within 500 km of Tulsa indicates that 1977 had an unusually low number of high-pressure systems (Table 3.16) and that their influence was comparatively short-lived. For the period, August seemed to have fewer occurrences of high-pressure systems, but their effect was longer lasting. September had more anticyclones, but they were rather fast moving.

## 3.1.2 Air Transport and Vertical Structure

### 3.1.2.1 Mesoscale Transport--

Hourly average wind speed and direction were compiled for the Liberty Mounds, Post Office, Skiatook, and Wynona stations and combined with the hourly wind speed and direction reported at Tulsa International Airport. These data were used to help define the characteristics of the airflow about the study area. Of principal interest were the air parcel trajectories associated with daily maximum ozone concentration and the movement of air out of the urban Tulsa area when precursor emissions were greatest.

Hourly wind data were tabulated for those five locations during the period 0600 to 1900 CST each day and were normalized to a 50-m altitude using the power law wind profile equation$^{(1)}$

$$v(z)/v(z_0)=(z/z_0)^p ,$$

where $z_0$ is the altitude of the measurement. To account for difference in surface roughness, $p = 2/7$ was used at the urban locations while $p = 1/7$ was used at the rural locations(2). The wind direction was held constant as altitude changed.

Both analyses used the time-space weighted interpolation first developed by Barnes(2) and modified by Bach(3). The interpolation uses a weight function of the form

$$\exp \{- (r^2/4k^2 + t^2/4v^2)\} ,$$

when r is the distance from the point in question to an observation and t is the time difference between the observation and the analysis time. Specifically, $k = 12.7$ km and $v = 1$ hour were used in this analysis. In all cases, only those observations for which

$$(r/2k)^2 + (t/2v)^2 \leq 8$$

were used. Each component of the wind was interpolated independently.

3.1.2.1.1 Air parcel trajectories--Air parcel movements were computed at half-hourly time increments for periods up to 6 hours using interpolated wind speed at the beginning of the time step. Trajectories were plotted for the air parcels arriving at four sampling sites at the time the daily maximum hourly $O_3$ was measured. The sites chosen were (a) the site of the maximum $O_3$; (b) Liberty Mounds, Post Office, and Vera; and (c) Wynona when the system maximum $O_3$ occurred at one of the previous sites. The trajectories are plotted on maps showing the sampling sites, the $O_3$ concentrations present at the arrival time of the trajectory, the date and time of arrival, and an outline of the Tulsa city limits. Appropriate trajectories are shown in case study analysis; all are shown in Appendix A.

3.1.2.1.2 Urban plume analyses--The urban plume analyses depict the 6-hour movement of air initially over Tulsa at 0600, 0900, 1200, and 1500 CST on each case study day. The urban area was characterized by a cross-hatched quadrilateral covering the city. The vertices of the area were moved in half-hourly increments at the speed and direction of the local wind vector interpolated from the wind observations. The movement of the area plume is shown in the figures for hourly increments for up to 6 hours, or until one vertex was out of the map area. The sequence of cross-hatched areas depicts the time that a given area was affected by the air initially over the Tulsa urban area at the given start hour. Those figures are presented with the case study analyses.

The distortion of the area indicates the divergence, vorticity, and deformation of the analyzed wind fields. Over-plotting of successive hourly position indicates slower moving, stagnating conditions. Occasionally, the area tends to collapse into a single line, suggesting that two parcels occupy the same space at the same time. That physically unrealistic condition probably results from a lack of data or an inhomogeneous wind distribution.

#### 3.1.2.2 Synoptic-Scale Transport--

Synoptic-scale air parcel trajectories were computed for air parcels arriving at Tulsa and Oklahoma City, Little Rock, and Kansas City. These trajectories were developed from National Weather Service rawinsonde data, vertically averaged over the lowest 2 km of the atmosphere, using a technique previously described by Bach(4). The trajectories were computed for arrival at 0600 and 1600 CST daily and depict the movement of the arriving parcel over the previous 48 hours. The complete plotted set of trajectories is given in Appendix B. Specific trajectories are discussed in the case studies. Because Oklahoma City trajectories are very similar to those for Tulsa, they were omitted from the plots for clarity of the figures.

The trajectories were stratified by the occurrence of high and low maximum daily ozone within the measuring network. The criteria for high or low ozone were developed by plotting the cumulative frequency distribution of maximum daily ozone on log probability paper. The high values exceed one standard deviation greater than the mean and the low values are less than one standard deviation less than the mean.

The plot of the 1600 CST trajectories associated with high and low ozone is shown in Figure 3.1. The results of this analysis are no different from similar analyses. Low ozone is found to generally occur with fast-moving air parcels trajectories while high ozone is found with slow-moving air. The passage of the air over urban areas seems immaterial to the ozone content as measured in Tulsa.

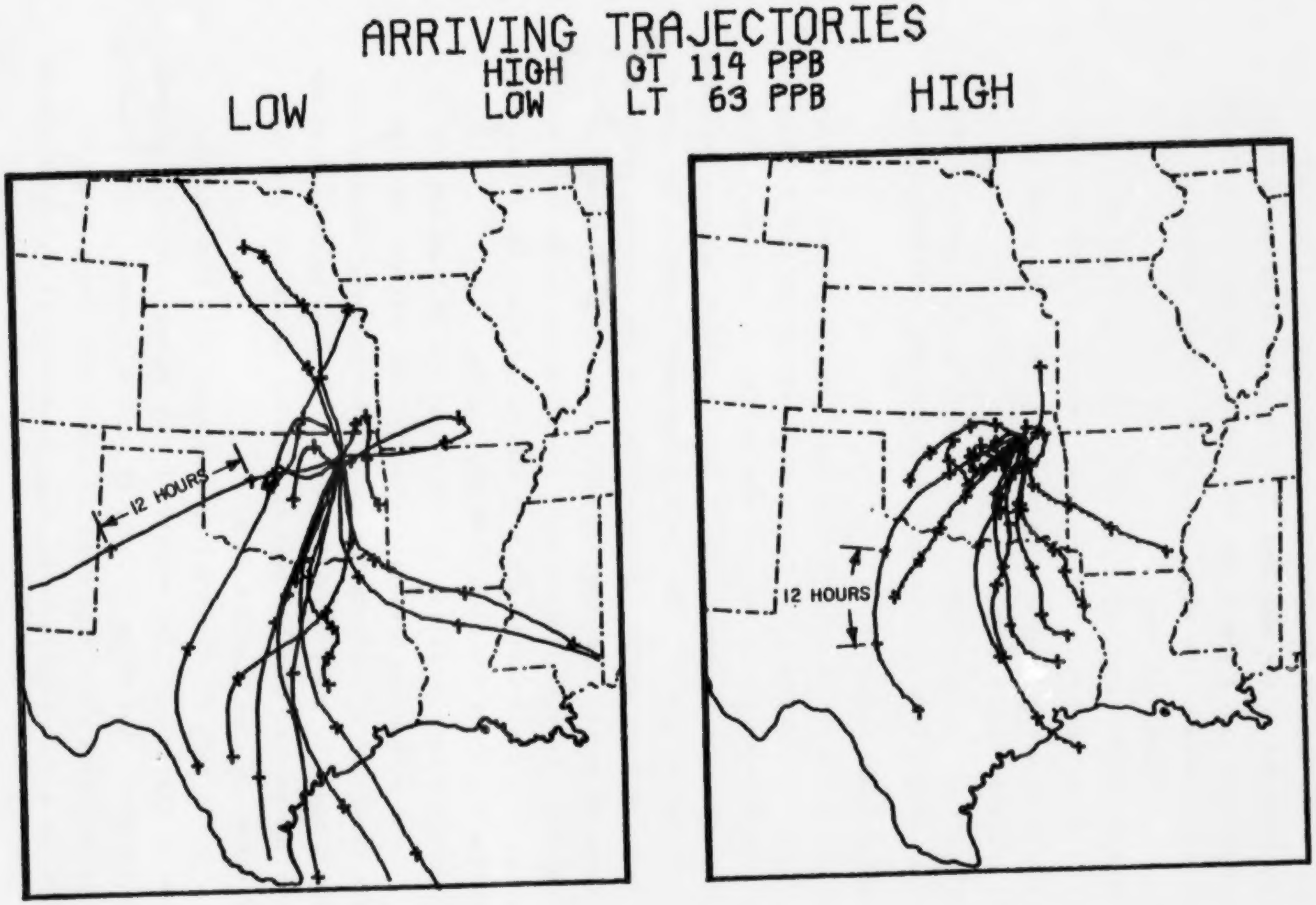

ARRIVING TRAJECTORIES
HIGH GT 114 PPB
LOW LT 63 PPB
LOW
HIGH
12 HOURS
12 HOURS

Figure 3.1. Arriving synoptic trajectories associated with low and high concentrations of ozone.

3.1.2.3 Sounding Analyses--

The vertical distribution of potential temperature and the water vapor mixing ratio were plotted for each case study day. These distributions were derived from the 0600 and 1800 CST rawinsonde data taken at Oklahoma City, 160 km southwest of Tulsa.

The potential temperature, $\theta$, is given by

$$\theta = T\ (1000/p)^{2/7} ,$$

where T is the ambient temperature (K) and p is the air pressure (mb). It represents the entropy of an air parcel and is conserved in adiabatic processes. Its vertical gradient, $\partial\theta/\partial z$, is directly proportional to the static stability of the air; therefore, the shape of its vertical profile immediately indicates the stability of the air.

The water vapor mixing ratio, R, is expressed in grams of water vapor per kilogram of dry air. In adiabatic motion, R is also conserved. Since water vapor is gaseous and has a ground source, the degree of mixing in the lower atmosphere should be indicated by the R profile. The mixing depth should be indicated by the altitude at which the R profile changes from a nearly constant value to a decreasing value with altitude.

The plotted profiles to 4 km for each case study day and the first twenty observations in the rawinsonde report are in Appendix C.

Analysis of the morning inversion characteristics and the afternoon mixing height(5) for case study days are summarized in Table 3-17.

## 3.2 EXAMINATION OF MEAN MONTHLY POLLUTANT DISTRIBUTIONS

### 3.2.1 Ozone

3.2.1.1 Variation of Ozone Diurnal Plots by Month--

A mean diurnal curve by month results when monthly average values of pollutant concentration for each hour of the day are plotted. The graph is a diurnal composite of all of the days in that month. Comparison of features of such graphs for different sites and months gives information on the urban or rural character of the air at the site and the variation of pollut-

TABLE 3.17. SOUNDING ANALYSES; CASE STUDY DAYS

| | Morning | | Afternoon |
|---|---|---|---|
| Date | Inversion top* (m, MSL) | Strength† (°C) | mixing depth (m,MSL) |
| July 21 | 762 | 6.1 | 1,870 |
| 22 | 595 | 4.4 | 1,940 |
| 23 | 594 | 5.9 | 3,030 |
| 24 | 858 | 8.2 | 3,594 |
| 25 | 1,002 | 10.1 | 3,720 |
| 28 | 1,045 | 4.7 | 800‡ |
| 29 | 494 | 2.9 | 2,140 |
| 30 | 652 | 6.9 | 2,195‡ |
| Aug 2 | 518 | 2.4 | 2,910 |
| 3 | 598 | 5.2 | 2,790 |
| 4 | 722 | 5.6 | 2,560 |
| 5 | 727 | 5.8 | 2,580 |
| Sept 2 | 535 | 8.0 | 2,000 |
| 3 | 509 | 7.2 | 2,955 |

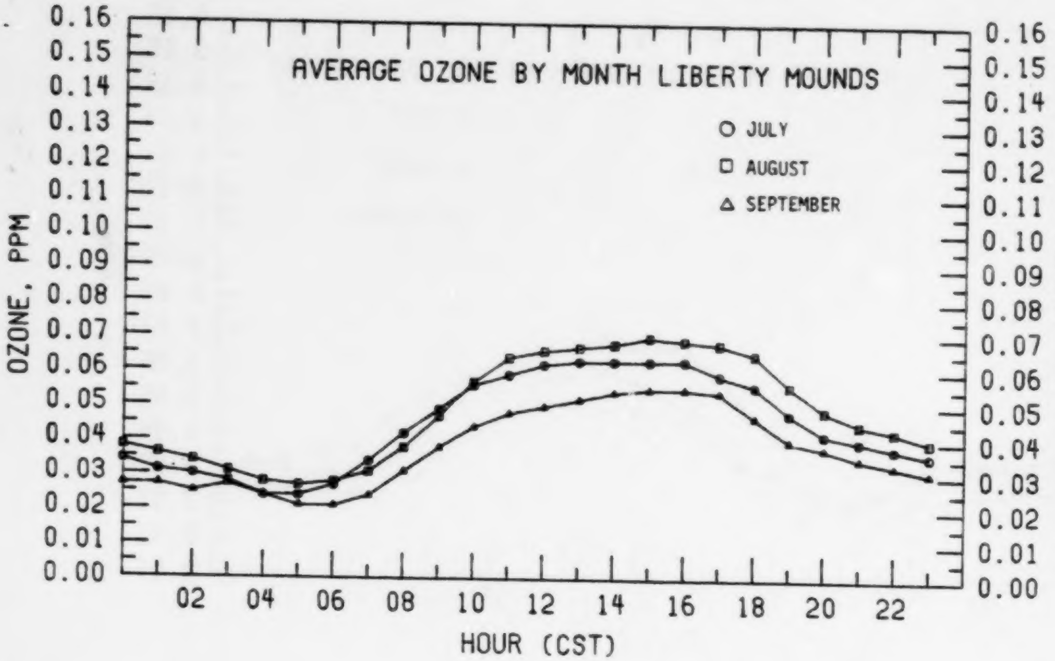
*Altitude at which $-dT/dz > 6.5°C/km$.

†Difference of potential temperature at the inversion top at ground (a measure of the diabatic heating needed to dissipate the inversion).

‡Rawinsonde surface temperature exceeded maximum daily temperature and was used in the calculation.

ant concentrations from month to month. Figure 3.2 shows the mean diurnal plots by month for the eight ozone monitoring sites maintained by RTI in the Tulsa study area.

When the three monthly diurnal ozone plots (July, August, and September 1977) are compared, one feature is immediately evident. The maximum amplitude of the curves decreases from July to August to September for six of the eight sites. In terms of photochemical production of ozone, this finding is expected since sunlight intensity and total minutes of sunshine are decreasing from month to month. The two exceptions to this order of ozone amplitudes are the background site, Liberty Mounds (which has an August diurnal ozone plot of greater magnitude than that of July), and Skiatook Lake (which has diurnal plots for July and August that are very similar). At each site the September diurnal plot was of lowest amplitude for the 3-month period.



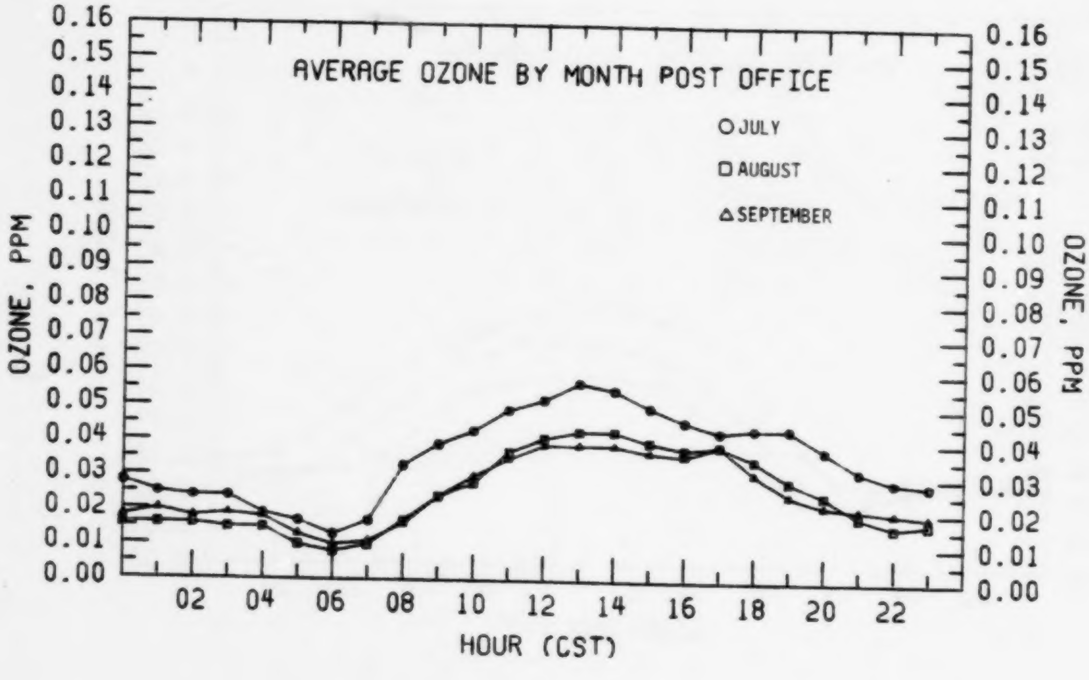
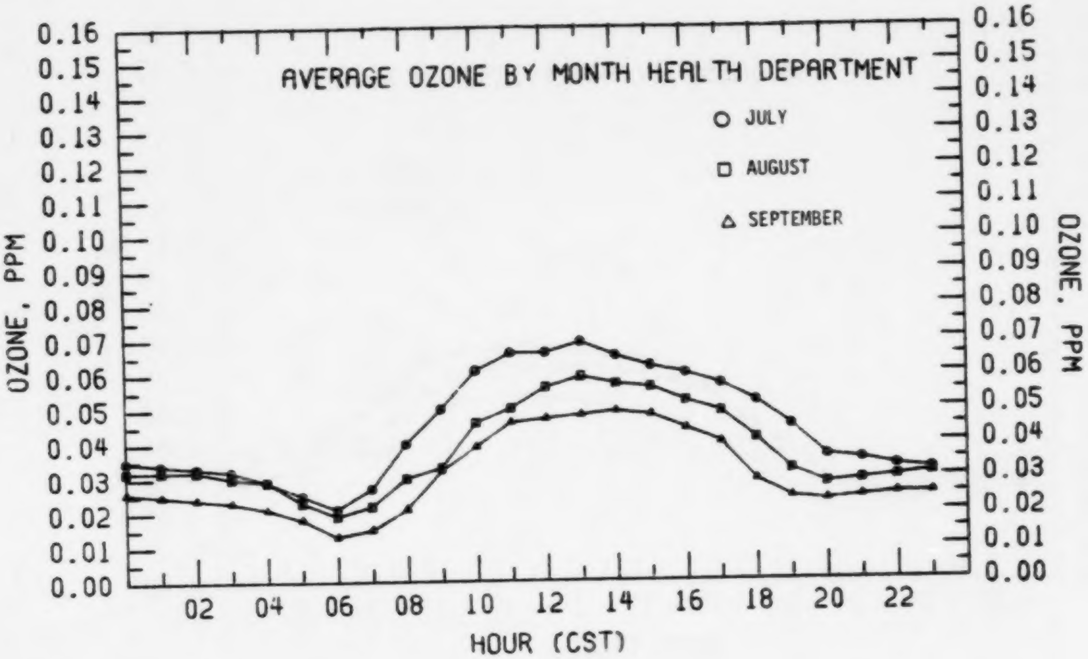


Figure 3.2. Mean monthly diurnal ozone for sites in the Tulsa area.



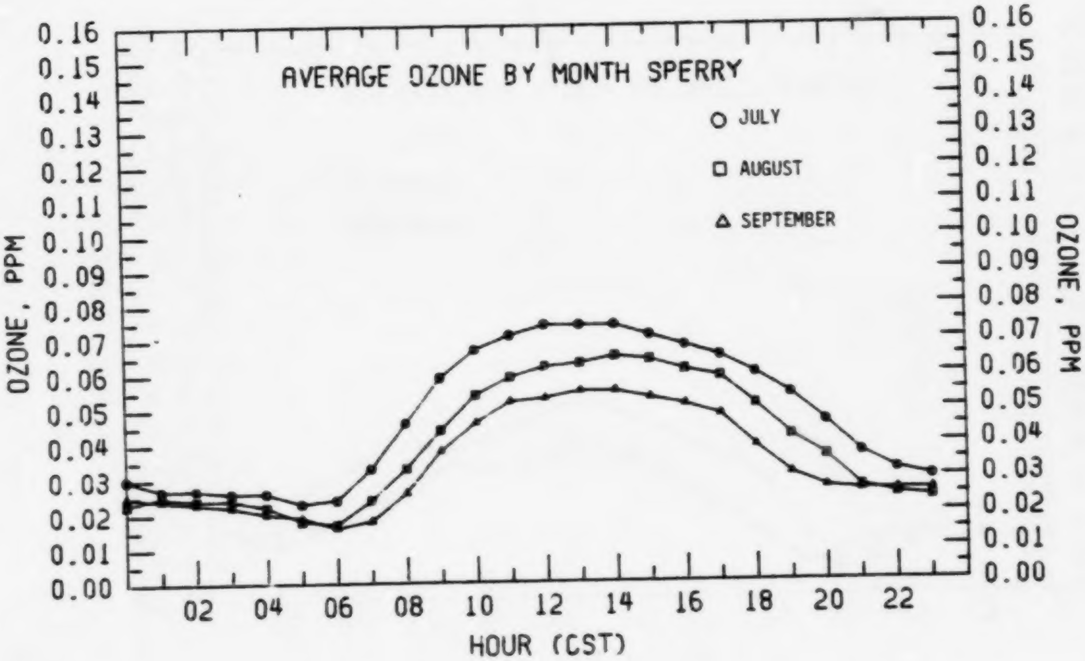
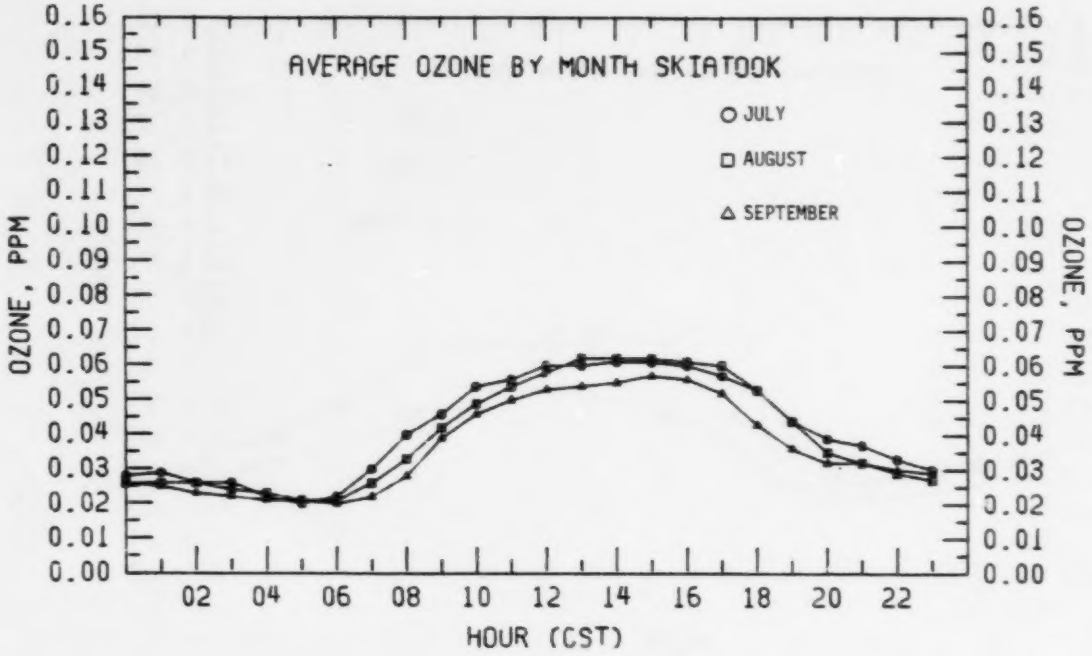


Figure 3.2. Mean monthly diurnal ozone for sites in the Tulsa area (continued).



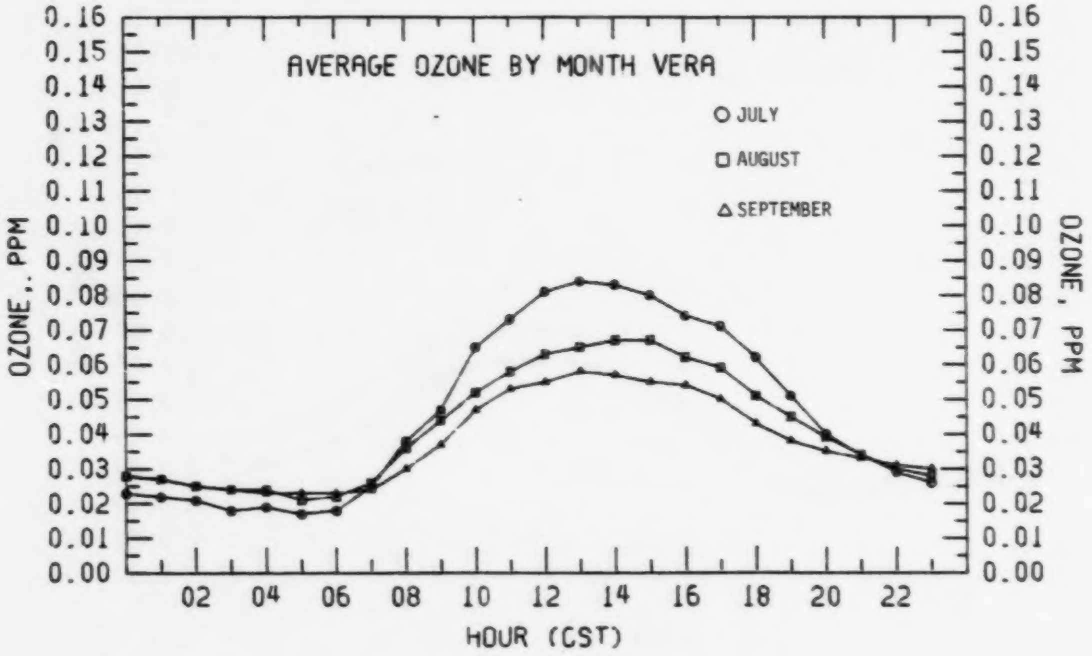
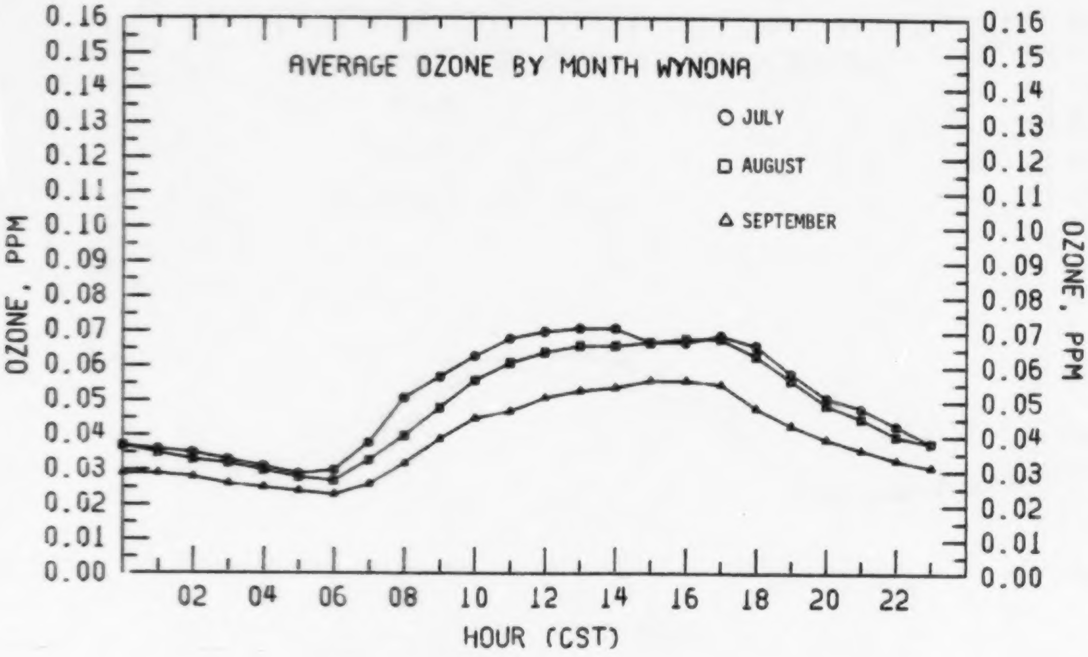


Figure 3.2. Mean monthly diurnal ozone for sites in the Tulsa area (continued).



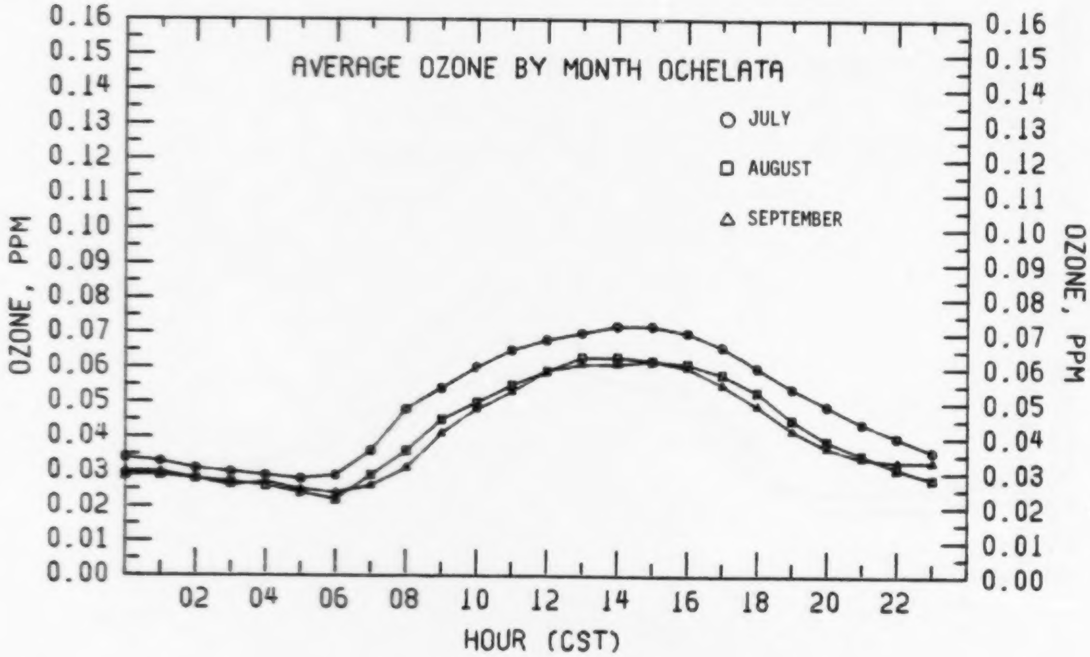


Figure 3.2. Mean monthly diurnal ozone for sites in the Tulsa area (continued).

Minimum average values of ozone also fell to lower values from July to August to September at each site.

The northern sites usually rank in the top five positions of average diurnal ozone maximum. One exception is the southern site, Liberty Mounds, which ranks first in maximum ozone in August; however, the concentration was not much greater than those recorded at the Wynona or Sperry sites. The urban core site, the Post Office, always ranks last in average maximum ozone as would be expected for a location with air containing high levels of ozone-destructive materials such as nitric oxide; this site also attains the lowest average minimum ozone level.

3.2.1.2 Examination of Ozone Frequency Distributions--

Bar graph representations of frequency distributions of ozone concentration in 0.01-ppm increments for July, August, and September for each site are given in Volume I of this report. Each bar graph shows the number of hourly observations for each range and the percentage of all hours for the month represented by the number of observations.

Several approaches are employed to evaluate and compare the frequency distributions for the different sites. The first approach is to compare the percentage of hours that have ozone concentrations greater than the then existing NAAQS of 0.08 ppm and less than a low value of 0.03 ppm. For the month of July, four of the five northern sites had a higher percentage of ozone concentration values greater than 0.08 ppm than either the southern site or the city sites. The exception is the Skiatook Lake site, which had only 2.0 percent of its hourly values above 0.08 ppm--the lowest percentage for all sites for July. The Vera site had the highest (17.5 percent) number of values in excess of 0.08 ppm. Next in line is Wynona with 14.5 percent; Sperry is third with 7.5 percent. Values above 0.08 ppm occurred three to four times more frequently at Vera than at sites in or south of the city. These findings suggest the influence of the urban plume on the Vera site since wind direction is generally from the south.

The distribution of values recorded during August generally shows that the percentage of ozone values above 0.08 ppm declined; furthermore, the percentage of values below 0.03 ppm increased. The most striking feature of the August distributions, as compared to those of July, is that the southern site, Liberty Mounds, had the highest percentage of ozone hourly values greater than the NAAQS with 9.6 percent. Wynona is second at 7.6 percent; Skiatook Lake is third with 7.0 percent. All sites outside the city had a greater number of hourly values above 0.08 ppm than did the two city sites.

During September, the frequency of hours when ozone was in excess of 0.08 ppm declined further with respect to the preceding month. The percentage of values less than 0.03 ppm generally increased with respect to values in August. The highest percentage of values above 0.08 ppm in September was 4.4 at Ochelata; second highest was 3.0 at Vera; third highest was 2.0 at Sperry.

### 3.2.2 Oxides of Nitrogen

#### 3.2.2.1 General--

Monthly average concentration levels of nitric oxide, NO, are quite low (7 ppb or less) at seven of the sites in the Tulsa area. Such concentrations are at or below the minimum detectable limit for the analyzers used in this study. Highest concentrations were recorded at the downtown Post Office site, which is close to primary NO emitters such as automobile traffic, railroads, and two petroleum refineries. This site had monthly average NO concentrations of 0.022, 0.034, and 0.023 ppm for July, August, and September, respectively. Nitrogen dioxide monthly average concentration values can be classed in three groups. Highest average values are recorded at the downtown Post Office site (0.024 to 0.029 ppm); second highest values are recorded at the Health Department (0.014 to 0.015 ppm) and Sperry (0.008 to 0.01 ppm); other sites have average monthly values ranging from 0.003 to 0.009 ppm. Table 3.18 lists the mean monthly values.

The 0600 to 0900 local daylight time monthly average values for $NO_x$ are summarized in Table 3.19. This time frame (0500 to 0800 CST) is of interest since it is during this period that early morning traffic buildup and other activities associated with a city are at their maximum (with corresponding maximum levels of oxides of nitrogen emissions). It is also the time during which photochemical production of ozone begins.

Mean monthly 0600-0900 CDT $NO_x$ values were greatest at the Tulsa Post Office site, and averaged 0.065 ppm over the 3-month period. As compared to

TABLE 3.18. **MEAN MONTHLY CONCENTRATIONS (PPM) OF NO AND $NO_2$**

| Site | Nitric Oxide | | | Nitrogen Dioxide | | |
|---|---|---|---|---|---|---|
| | July | August | September | July | August | September |
| Liberty Mounds | 0.001 | 0.001 | 0.001 | 0.006 | 0.003 | 0.003 |
| Post Office | 0.022 | 0.034 | 0.023 | 0.029 | 0.028 | 0.024 |
| Tulsa City/County Health Department | 0.002 | 0.004 | 0.007 | 0.014 | 0.014 | 0.015 |
| Sperry | 0.004 | 0.003 | 0.005 | 0.009 | 0.010 | 0.008 |
| Skiatook Lake | 0.000 | 0.000 | 0.000 | 0.004 | 0.005 | 0.004 |
| Vera | 0.002 | 0.003 | 0.001 | 0.004 | 0.008 | 0.009 |
| Wynona | 0.000 | 0.001 | 0.000 | 0.005 | 0.005 | 0.002 |
| Ochelata | 0.003 | 0.001 | 0.000 | 0.006 | 0.005 | 0.005 |

TABLE 3.19. MEAN 0600-0900 CDT $NO_x$ CONCENTRATIONS BY MONTH AND ENTIRE PERIOD FOR MONITORING SITES, TULSA, OKLAHOMA, 1977

| | $NO_x$, ppm | | | |
|---|---|---|---|---|
| | July | August | September | Total period |
| Liberty Mounds | 0.009 | 0.006 | 0.005 | 0.007 |
| Tulsa Post Office | 0.065 | 0.073 | 0.055 | 0.065 |
| Tulsa City/County Health Department | 0.019 | 0.028 | 0.034 | 0.027 |
| Sperry | 0.016 | 0.016 | 0.020 | 0.017 |
| Skiatook Lake | 0.005 | 0.005 | 0.004 | 0.005 |
| Vera | 0.006 | 0.012 | 0.012 | 0.011 |
| Wynona | 0.006 | 0.006 | 0.004 | 0.005 |
| Ochelata | 0.011 | 0.007 | 0.005 | 0.007 |

urban sites in other cities(6), Tulsa's 0600-0900 $NO_x$ average is not as high as central business district (CBD) locations in Houston (0.156 ppm) or Los Angeles (0.147 ppm). Its average $NO_x$ value is similar to that of El Paso (0.067 ppm) or to a composite value for seven sites near the CBD of St. Louis (0.077 ppm). The second highest 3-month average was 0.027 ppm and was recorded at the Health Department site. This concentration is of similar magnitude to those at other suburban sites such as the Ascarte Park site in El Paso, Texas, which has a mean 0600-0900 value of 0.028 ppm.

### 3.2.2.2 Monthly Mean Diurnal Behavior of NO and $NO_2$--

Of the three city sites (Post Office, Health Department, and Sperry), average hourly levels of NO and $NO_2$ were highest at the Post Office site. All three sites had higher average values than the remaining five sites. The NO plot for the Post Office shows that there was continual injection of this pollutant throughout the day. Maximum hourly average values between 0.035 and 0.049 ppm were attained during the morning traffic rush hours of 0500-0800 CST. Values then declined during the morning due to the combined effects of lessened emissions, reaction of NO with ozone, and transport/ dilution. Early in the afternoon (around 1400) concentrations began to climb; this was most evident during the month of July when an average peak concentration of 0.037 ppm was attained at 1700. NO values began to fall off again at about 1600 or 1700 CST as the afternoon traffic diminished. However, average hourly values remained at 0.010 to 0.030 ppm on into the evening. Much lower NO values were recorded in the evening at the Health Department (~0.014 ppm) and Sperry (~0.06 ppm) locations than at the Post Office site.

At the Liberty Mounds, Skiatook Lake, Vera, and Ochelata sites, the diurnal curves for each month show values that are quite low for both NO and $NO_2$ (less than 0.012 ppm, with many average hourly values at 0.003 ppm). The diurnal plots show no regular pattern or curve. For each hourly average of the 3 months--July, August, and September--$NO_2$ concentrations averaged 0.008 ppm or below. A recurrent feature of these curves is that $NO_2$ concentrations were slightly higher in the early morning hours than during the daylight hours when good mixing had occurred.

Maximum average hourly values of $NO_2$ at Liberty Mounds, as taken from the diurnal curve, were 0.009, 0.005, and 0.004 ppm for July, August, and September, respectively. These values are similar to diurnal curve $NO_2$ maxima recorded in a previous EPA study at rural sites(7). Maximum $NO_2$ values from a diurnal plot covering the period June 27 through October 31, 1975, were 0.004, 0.003, 0.000 (below minimum detectable limit), and 0.004 at sites near Bradford, Pennsylvania, Creston, Iowa, Wolf Point, Montana, and DeRidder, Louisiana, respectively.

$NO_2$ average values at the Post Office site were fairly high throughout the day. Values for each month are closely grouped. Maximum values occurred early in the morning between 0700 and 0900 and ranged between 0.026 and 0.038 ppm. During this time NO was being emitted in larger quantities and was quickly reacting with residual and newly formed ozone to produce $NO_2$. A slight fall-off in $NO_2$ values occurred at about midday (1200 to 1300). During this time of high sunlight, NO emissions lessened and $NO_2$ photodissociation and other reactions were prevalent. By 1500, $NO_2$ levels had peaked again to a maximum of 0.032 ppm.

The Health Department and Sperry sites each showed a fairly uniform $NO_2$ concentration pattern for each month. Values were elevated in the early morning hours (~0.022 ppm at the Health Department site and ~0.012 ppm at the Sperry site), fell off gradually to a low point at about 1300, and then slowly climbed to the highest average level for the day later in the evening (~0.024 ppm at 2000 at the Health Department site and ~0.014 ppm at hour 2100 at the Sperry site).

### 3.2.3 Nonmethane Hydrocarbons

Total hydrocarbons, nonmethane hydrocarbons, and methane were measured by use of the Beckman Model 6800 Air Quality Chromatograph at three sites in the Tulsa area. These sites were the urban core site at the Post Office, the suburban site at the Tulsa City/County Health Department, and a rural site, Wynona. Diurnal plots for the total periods of hydrocarbon measurement were constructed and examined. Note that the dates of the measurements are not identical from site to site.

Mean diurnal concentrations of NMHC were highest at the Tulsa Post Office. An average maximum value of 0.65 ppmC occurred at 0600 CST; the minimum value was 0.30 ppmC and occurred during hour 1800. There was a small increase in NMHC concentration during the day from 1200 to 1400, which could be attributed to midday vehicular activity in the urban core area of the city. No similar patterns for this time frame were observed at either the Health Department or Wynona site. The Health Department NMHC diurnal did exhibit a steady buildup of hydrocarbons starting at 0.10 ppmC at hour 1300 and maximizing at 0.39 ppmC at hour 1900. Values then fell off to a minimum point of 0.10 ppmC at hour 0200. Concentrations at the Post Office and Wynona sites were increasing during evening hours and continued to increase until early morning. In contrast, the Health Department's concentration values fell off during the evening (after hour 1900) and increased only slightly in the early morning hours of 0200 through 0700.

The Post Office site NMHC diurnal is similar to that recorded by similar instrumentation in the St. Louis RAPS network from June through October 1976(8). However, values at the Tulsa site did not fall to as low a point as at sites in St. Louis.

The NMHC values recorded at the rural site, Wynona, were remarkably high during the evening hours with a peak value of 0.61 ppmC in the 0500 hour. Between the hour of 0600 and 0700, the NMHC average concentration decreased dramatically (the Post Office site was also decreasing, but less rapidly). The buildup of NMHC at this site was probably due to a combination of geogenic and anthropogenic emissions into a space beneath an inversion layer where low wind speeds are prevalent.

## 3.3 DISCUSSION OF STRATIFIED DATA BASE

### 3.3.1 Introduction

Of the eight monitoring sites in the RTI Tulsa network, one was to the south of the city, two were in the city, and five were to the north of the city. Winds in eastern Oklahoma were generally from the south. Thus, the southern site was usually exposed to what could be termed nonurban air; the northern sites were, on many days, exposed to air that had passed over the Tulsa metropolitan area that could be called urban air. This section of the report is concerned with the comparison of data for ozone and oxides of nitrogen (there were too few hydrocarbon samples at northern sites to establish a stratification) for days that have been divided into urban and nonurban categories. Such a stratification gives an average picture of the overall ozone and ozone-precursor spatial and temporal distributions in the vicinity of Tulsa.

Stratifications were made on a day-by-day basis for the six sites surrounding Tulsa. The two city sites are considered to be always under the influence of urban air. The primary urban/nonurban stratification was made on the basis of two major criteria: (1) the average vector wind direction for the hours 0700 through 1600 CST as measured at the site under consideration and at other sites; and, (2) examination of the afternoon synoptic and mesoscale trajectories insofar as their temporal and spatial resolution permits.

To decide what would constitute an urban-influenced day, the following strategy was used. On a map (U.S. Geological Survey, 1:250,000) two lines were drawn from the point of location of each site. One line extended from the site to the eastern border of the city; the other line extended from the site to Tulsa's western border. The number of degrees (arc) swept out by these two lines was determined. To account for urban plume broadening and small variations in wind direction, a 10-degree span was added to the eastern and western limits. This process gave the following degree ranges in which air parcels would be classified as urban- or nonurban-influenced.

| | Urban | Nonurban |
|---|---|---|
| Liberty Mounds | 335° - 037° | 038° - 334° |
| Sperry | 125° - 218° | 219° - 124° |
| Skiatook Lake | 116° - 180° | 181° - 115° |
| Vera | 160° - 220° | 221° - 159° |
| Wynona | 123° - 166° | 167° - 122° |
| Ochelata | 152° - 201° | 202° - 151° |

By using this scheme, all days were classified as either urban or nonurban. Table 3.20 summarizes those days classified as urban-influenced.

In particular borderline cases, the individual hours of wind direction data were examined, and if the morning hours showed consistent direction, the day was classified accordingly.

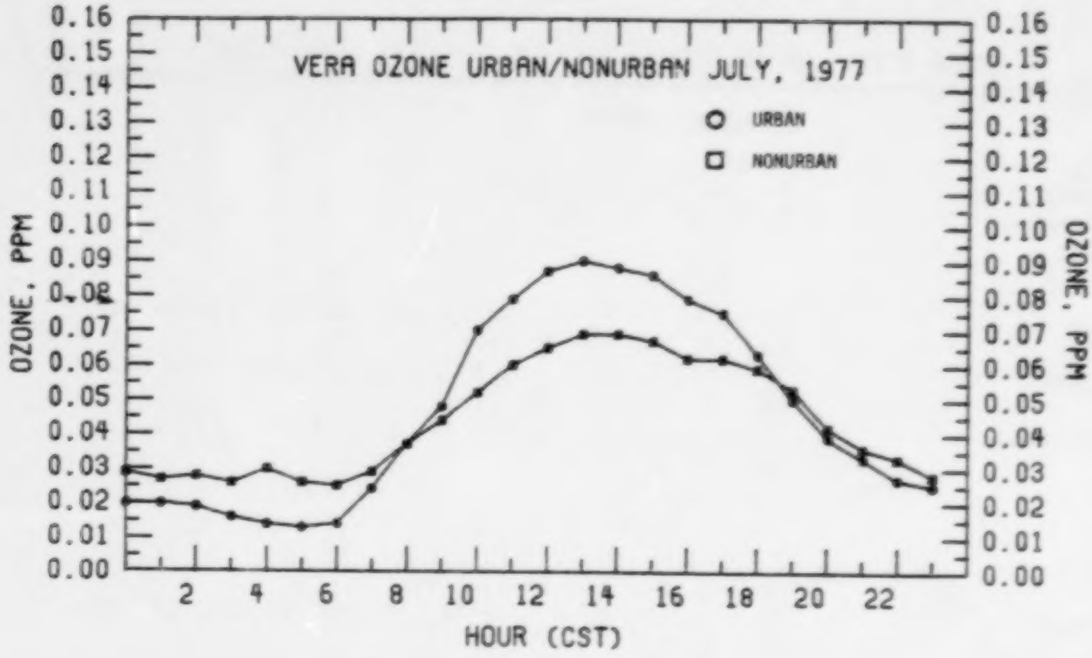
### 3.3.2 Urban and Nonurban Ozone

Mean hourly values of ozone were calculated for each site for the months July, August, and September for urban and nonurban sets of days. From these, the mean monthly urban and nonurban diurnal curves were constructed for the northern sites, Sperry, Vera, and Ochelata. In each case there is a significant difference between the urban and nonurban curves. The urban curve portrays much higher ozone concentrations during the midday hours than does the curve for nonurban days. This probably reflects the enhanced ozone production in air parcels that passed over Tulsa. Figure 3.3 shows the mean diurnal curves for urban- and nonurban-influenced days at the Vera site for July, August, and September. As was also true for Sperry and Ochelata, the highest average urban or nonurban ozone concentrations at Vera were recorded in July, followed by August and September. One possibility for this trend would be the diminishing intensity of solar radiation. A statistical test of significance (t-test) at the 95 percent confidence level showed that, for individual months and for the 3-month period, the averages of daily maximum values of ozone for urban days were significantly different from the average of daily maximum values for nonurban days. Furthermore, the mean of ozone concentrations during the 4 hours having the highest average concentrations of ozone was statistically significantly different

## TABLE 3.20. URBAN-INFLUENCED DAYS AT SITES NEAR TULSA

| | |
|---|---|
| | Liberty Mounds |
| July | 1, 27 |
| August | 11, 12, 13, 17, 24, 29 |
| September | 5, 6, 13, 14, 19, 24 |
| | Sperry |
| July | 2, 3, 4, 5, 6, 7, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 23, 30 |
| August | 2, 3, 4, 5, 6, 7, 8, 9, 10, 14, 15, 16, 20, 22, 23, 25, 26, 27, 30, 31 |
| September | 1, 2, 3, 4, 8, 11, 12, 16, 17, 18, 20, 21, 22, 23, 26, 30 |
| | Vera |
| July | 2, 3, 4, 5, 6, 7, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 23, 24, 28, 30 |
| August | 3, 5, 6, 7, 8, 9, 10, 14, 16, 20, 22, 23, 25, 26 27, 30, 31 |
| September | 1, 2, 3, 4, 8, 12, 16, 17, 18, 20, 21, 22, 23, 26, 30 |
| | Ochelata |
| July | 2, 7, 10, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21, 28, 30 |
| August | 3, 4, 5, 6, 7, 14, 15, 20, 22, 25, 26, 27, 30, 31 |
| September | 1, 2, 3, 8, 12, 16, 17, 18, 20, 21, 22, 23, 26, 30 |
| | Skiatook Lake |
| July | 15, 19 |
| August | 3, 4, 14, 15, 19, 20, 22, 25 |
| September | 1, 2, 3, 8, 11, 16, 20, 21, 22, 26 |
| | Wynona |
| July | |
| August | 4, 14, 15, 19, 22, 25 |
| September | 1, 11, 16, 20, 21, 22 |

for the urban and nonurban data sets. Table 3.21 lists the average values and the number of cases for the 3-month period.



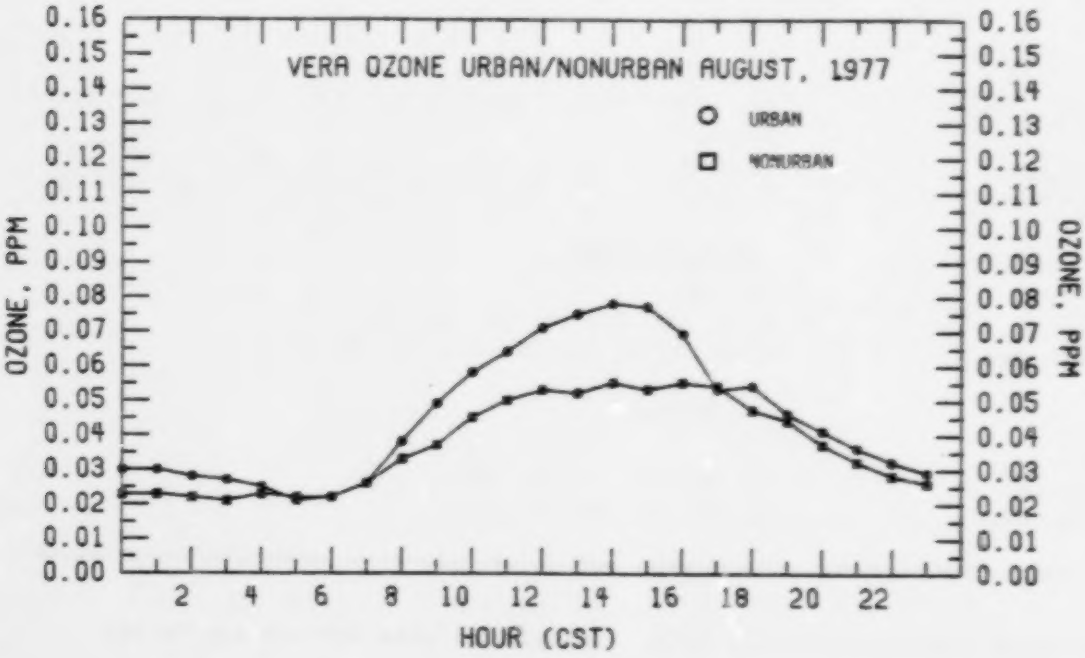


Figure 3.3. Mean monthly diurnal ozone for urban and nonurban influenced days at the Vera site.

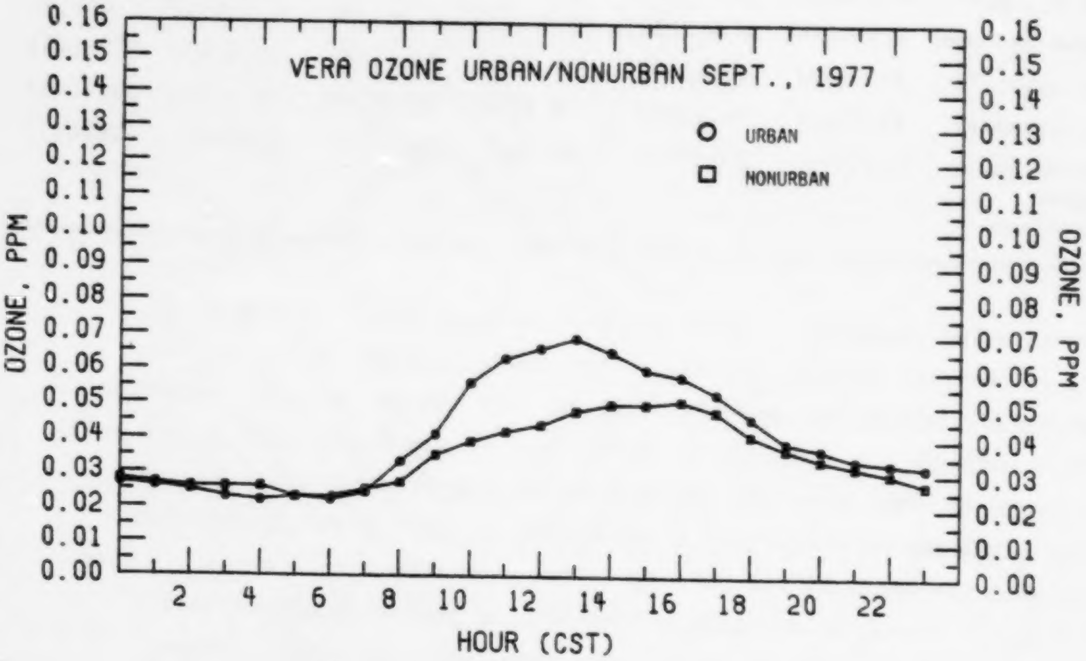


Figure 3.3. Mean monthly diurnal ozone for urban and nonurban influenced days at the Vera site (continued).

TABLE 3.21. AVERAGE VALUES FOR OZONE, TEMPERATURE, PERCENT SUNSHINE, AND SOLAR RADIATION

| | Sperry | | Vera | | Ochelata | |
|---|---|---|---|---|---|---|
| | Urban | Rural | Urban | Rural | Urban | Rural |
| Maximum $O_3$, ppm | 0.080(53) | 0.060(34) | 0.087(54) | 0.061(38) | 0.082(42) | 0.062(43) |
| 4-hr mean $O_3$, ppm | 0.070(54) | 0.051(34) | 0.077(54) | 0.054(38) | 0.073(42) | 0.056(45) |
| Maximum temp, °F | 93.1(56) | 84.6(36) | 93.4(54) | 84.6(38) | 92.4(43) | 87.5(49) |
| Percent sunshine | 79.3(56) | 49.2(36) | 79.7(54) | 50.3(38) | 78.3(43) | 58.1(49) |
| Cumulative solar radiation, langleys/min | 549(54) | 367(35) | 559(52) | 363(37) | 534(42) | 426(47) |

Because the intensity of sunlight and the temperature are important factors in the photochemical production of ozone, average values of the maximum daily temperature, percent sunshine, and cumulative solar radiation were also compared for urban and nonurban days at the three sites (Table 3.21). It was found in most cases that the differences in average values for the meteorological parameters were also statistically significantly different. On days when the winds at the northern sites were from directions other than southerly, the averages for maximum temperature, percent sunshine, and cumulative solar radiation were all lower than their southerly, urban-influenced counterparts. In a further stratification, when 14 urban-influenced days at Vera were compared to 12 nonurban days that had similar cumulative solar radiation, the difference in the average ozone profiles was still significantly different, yet the meteorological parameters were not. This finding implies that enhanced concentrations of ozone at the northern sites are associated with air parcels that have passed over the urban area.

A further comparison was made between the upwind site, Liberty Mounds, and downwind sites for urban-influenced days that were common to Sperry, Vera, and Ochelata. Figure 3.4 shows the average monthly diurnal plots of these common days in July (14 days), August (11 days), and September (14 days). Average hourly ozone concentrations for the same days are shown for Liberty Mounds (these days are, of course, nonurban days at this site). Several features of these plots should be noted.

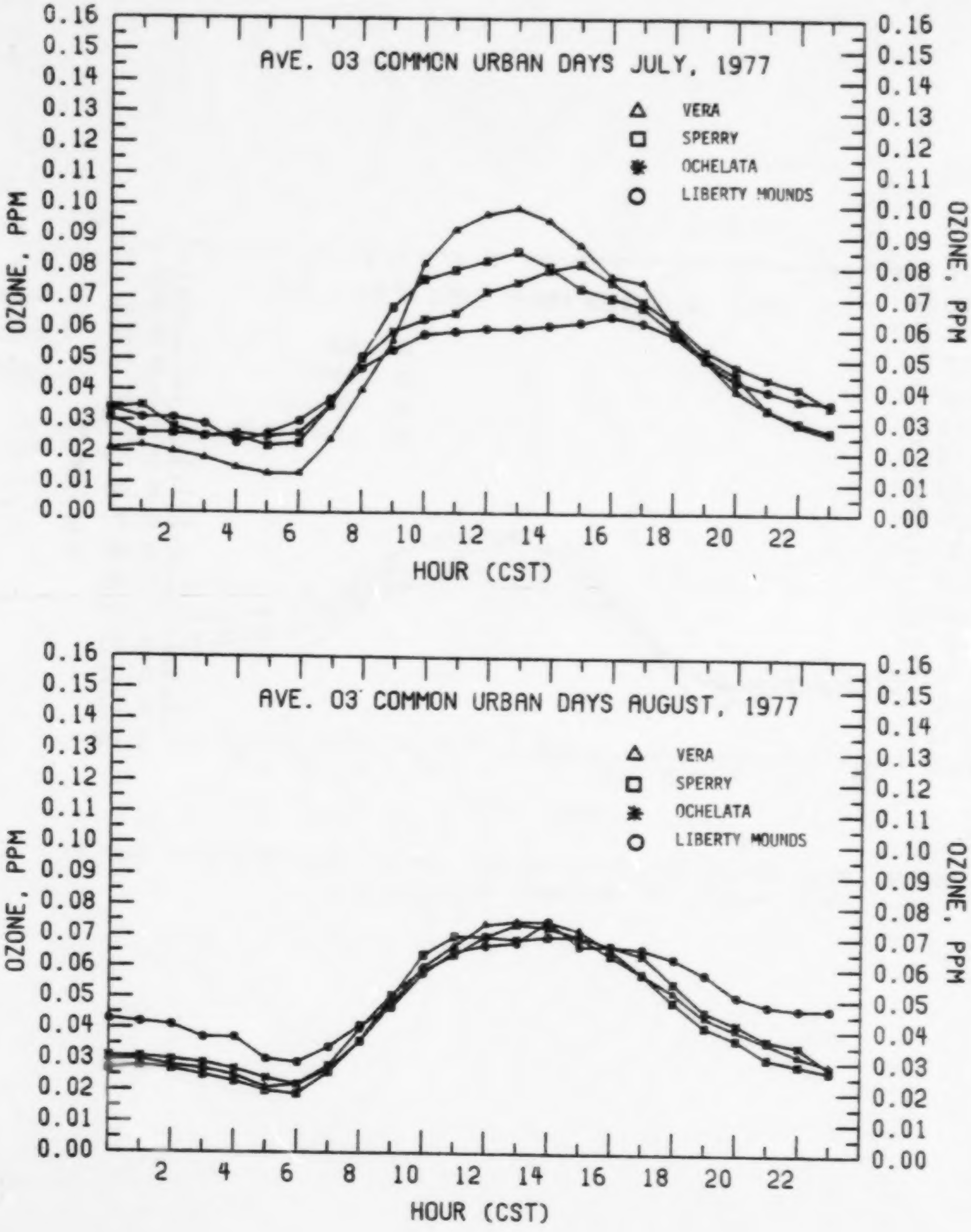


Figure 3.4. Mean monthly diurnal ozone for common urban influenced days in July, August, and September.

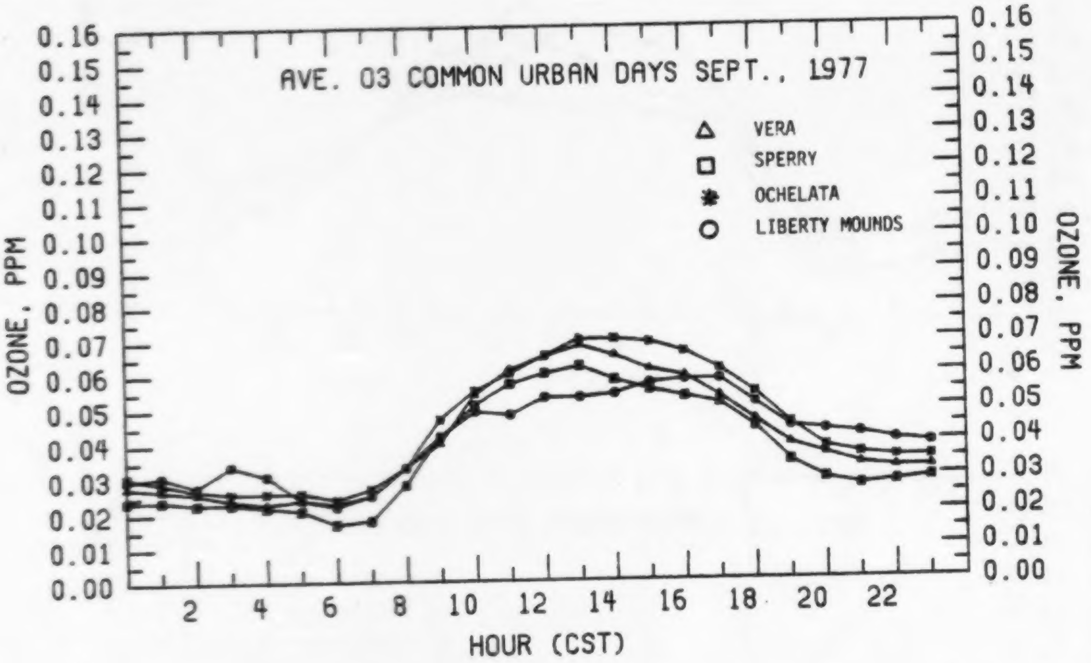


Figure 3.4. Mean monthly diurnal ozone for common urban influenced days in July, August, and September (continued).

For the month of July, the upwind background site, Liberty Mounds, displayed an average diurnal ozone curve typical of nonurban areas. The average minimum value was reached in the early morning (0400) and, as the inversion layer broke up and the combined effects of downward mixing of ozone from above the inversion and local photosynthesis of ozone occurred, the concentration rose gradually. The average concentration leveled off at about hour 1000 and persisted at or near this value until hour 1800. The average maximum value of 0.064 ppm occurred relatively late in the day at hour 1600.

In contrast, the diurnal curves for sites to the north of Tulsa show nighttime and early morning ozone concentrations that are generally lower and remain lower for a couple of hours longer than those of the background site (probably a consequence of ozone titration by urban-emitted ozone scavengers such as NO). At about hour 0600, the ozone concentrations began to climb at a rate much faster than those of Liberty Mounds and reached peak values considerably higher and earlier in the day than those of the background site. The diurnal curve of the urban-influenced site(s) is not flattened during the midday hours as is that of Liberty Mounds. Average peak ozone concentrations of 0.085 ppm and 0.099 ppm were reached at hour 1300 at the Sperry and Vera sites, respectively. The Ochelata average peak was 0.081 ppm and occurred somewhat later (hour 1500). The lag in the time of the occurrence of maximum ozone at Ochelata was probably a consequence of the increased travel time required for a given air parcel to reach the northernmost site.

Figure 3.4 also compares the mean diurnal curves for the 11 urban-influenced days in August that were common to Sperry, Vera, and Ochelata. In contrast to the July diurnal curves, the average maximum values are quite similar. The difference is probably largely due to lower percent sunshine for August days (74 as compared to 84 for July days) and higher morning wind speeds for common days in August (11.1 versus 9.2 mph). The Liberty Mounds curve displays features characteristic of a nonurban site: average concentrations of ozone were higher during the nighttime and predawn hours than are those of northern sites, and the curve is flatter than those of urban-influenced sites, showing that elevated ozone concentrations persisted longer. Except for a concentration excursion to 0.075 ppm at hour 1400, the average hourly afternoon values at Liberty Mounds were the lowest of the four sites. Sperry was next lowest, Ochelata somewhat higher, and Vera was highest. Figure 3.4 shows that the maximum average ozone attained in the system was at the Vera site.

The mean diurnal behavior of ozone for the 14 common days of September is shown in Figure 3.4. Of the four sites, ozone concentrations at Liberty Mounds were highest during the nighttime hours and lowest during the afternoon hours. An average maximum of 0.058 ppm occurred at hour 1700. Values at the urban-influenced downwind sites ascend in the order of Sperry, Vera, and Ochelata. The closer the site is to the urban area (and its ozone-destructive emissions) the lower is the average maximum concentration. Average values of 0.062, 0.068, and 0.070 ppm occurred at hour 1300 at Sperry, Vera, and Ochelata, respectively. Average morning solar radiation intensities for common September days was a third less than for July common days.

For the 3-month period, the average hourly maximum values for ozone for urban-influenced days at Sperry, Vera, and Ochelata were 0.077, 0.085, and 0.081 ppm, respectively. The average hourly maximum for the same days at Liberty Mounds was 0.068 ppm. The difference between each of the urban-influenced averages and the nonurban average is statistically significant at the 95 percent confidence level. This is to say, the probability that the difference could have occurred by chance is less than 5 percent.

### 3.3.3 Urban and Nonurban Oxides of Nitrogen

Concentration values for oxides of nitrogen ($NO$, $NO_2$, $NO_x$) were also examined for the stratified urban- and nonurban-influenced days. Table 3.22 presents average values for the time intervals 0500 through 0700 CST and 1000 through 1200 CST for urban-influenced days at the Sperry, Vera, and Ochelata sites. Values from the upwind site, Liberty Mounds, and one of the city sites, the Post Office, are included for comparison.

In all cases the concentration of $NO$, $NO_2$, or $NO_x$ was quite low at the upwind Liberty Mounds site. The highest average $NO_x$ concentration attained at this site was 0.010 ppm for early morning hours in July. As expected, the downtown Post Office site recorded much higher concentrations than Liberty Mounds during both time periods. The $NO$, $NO_2$, and $NO_x$ concentrations during the 1000-1200 averaging period at the Post Office site were in all cases somewhat higher than those recorded during the 0500 through 0700 CST

TABLE 3.22. AVERAGE NO, $NO_2$, AND $NO_x$ CONCENTRATIONS, ppm, ON URBAN-INFLUENCED DAYS COMMON TO SPERRY, VERA, AND OCHELATA

| | Hours 05, 06, 07 CST | | | Hours 10, 11, 12 CST | | |
|---|---|---|---|---|---|---|
| | NO | $NO_2$ | $NO_x$ | NO | $NO_2$ | $NO_x$ |
| Liberty Mounds | | | | | | |
| July | .001 | .009 | .010 | .001 | .006 | .007 |
| August | .002 | .003 | .005 | .002 | .002 | .004 |
| September | .003 | .004 | .007 | .001 | .002 | .003 |
| Post Office | | | | | | |
| July | .033 | .033 | .066 | .034 | .036 | .070 |
| August | .054 | .031 | .085 | .067 | .040 | .107 |
| September | .049 | .033 | .082 | .055 | .038 | .093 |
| Sperry | | | | | | |
| July | .006 | .015 | .021 | .004 | .008 | .012 |
| August | .007 | .012 | .019 | .002 | .010 | .012 |
| September | .014 | .010 | .024 | .003 | .008 | .011 |
| Vera | | | | | | |
| July | .001 | .006 | .007 | .003 | .004 | .007 |
| August | .004 | .009 | .013 | .002 | .008 | .010 |
| September | .002 | .010 | .012 | .001 | .010 | .011 |
| Ochelata | | | | | | |
| July | .004 | .009 | .013 | .002 | .005 | .007 |
| August | .002 | .007 | .009 | .001 | .004 | .005 |
| September | .000 | .006 | .006 | .000 | .004 | .004 |

period in spite of the expected greater mixing due to increased ventilation. Thus, it seems that when winds are from the south, concentrations of $NO_x$ in Tulsa are sustained and do not diminish after the morning traffic rush hours.

The Sperry, Vera, and Ochelata sites recorded NO, $NO_2$, and $NO_x$ concentrations that were sharply reduced as compared to those in the city (see Table 3.22). For the 0500 through 0700 CST time period, relative $NO_x$ concentrations were: Post Office, 1; Sperry, 0.28; Vera, 0.13; and Ochelata, 0.09. Average oxides of nitrogen values at Ochelata were not significantly different from those found at the upwind site, yet the ozone values were significantly

TABLE 3.23. AVERAGE NO, $NO_2$, AND $NO_x$ CONCENTRATIONS, ppm, ON NONURBAN-INFLUENCED DAYS AT SPERRY, VERA, AND OCHELATA

| | Hours 05, 06, 07 CST | | | Hours 10, 11, 12 CST | | |
|---|---|---|---|---|---|---|
| | NO | $NO_2$ | $NO_x$ | NO | $NO_2$ | $NO_x$ |
| Post Office | | | | | | |
| July | .019 | .031 | .050 | .008 | .023 | .031 |
| August | .025 | .022 | .047 | .008 | .017 | .025 |
| September | .014 | .020 | .034 | .006 | .017 | .023 |
| Sperry | | | | | | |
| July | .004 | .008 | .012 | .003 | .006 | .009 |
| August | .004 | .008 | .012 | .002 | .006 | .008 |
| September | .008 | .007 | .015 | .004 | .005 | .009 |
| Vera | | | | | | |
| July | .003 | .006 | .009 | .003 | .002 | .005 |
| August | .001 | .005 | .006 | .001 | .007 | .008 |
| September | .000 | .005 | .005 | .000 | .008 | .008 |
| Ochelata | | | | | | |
| July | .002 | .004 | .006 | .001 | .005 | .006 |
| August | .004 | .008 | .012 | .002 | .003 | .005 |
| September | .002 | .009 | .011 | .008 | .004 | .012 |

different. This tends to suggest that the concentrations of ozone attained at Ochelata are not dependent on $NO_x$ levels at that site, but rather are dependent on transport of photochemically active air parcels from the urban environs.

Table 3.23 presents similar data for nonurban days at Sperry, Vera, and Ochelata. The average concentrations for the CBD (Post Office) site for days judged to be nonurban at Sperry are also listed. On the whole, concentrations of NO, $NO_2$, and $NO_x$ were lower at each site in comparison to urban days. In fact, the values were about the same as those determined for nonurban-influenced days at Liberty Mounds. This suggests that $NO_x$ was not being transported into the study area at ground level.

An examination of the values of NO, $NO_2$, and $NO_x$ at the Post Office site for the days when the northern sites were classed as nonurban-influenced (i.e., northerly winds) shows that average values at the Post Office site are lower in the 0500-0700 samples than the average for urban-influenced days (i.e., southerly winds) and that the concentrations in the 1000-1200 period are lower than in the early morning time frame. This contrast elicits two comments. First, the bulk of the NO, $NO_2$, and $NO_x$ seems to originate in areas generally to the south of the Post Office site (the greater part of the urban area and industry is located to the south). Second, the sources of $NO_x$ to the south are such that their emissions of $NO_x$ continue throughout the morning hours. This suggests that continuous vehicular traffic and/or continuous industrial processes are responsible for an appreciable portion of the $NO_x$ measured at the Post Office site during the hours 1000, 1100, and 1200 when winds were southerly.

## 3.4 STATISTICAL RELATIONSHIP OF OZONE TO OTHER PARAMETERS

In this section, the relationships between daily maximum ozone concentrations and values of various meteorological and pollutant variables measured in Tulsa are examined. Table 3.24 is a listing of the summary statistics (mean values, standard deviations, maximum values, and the number of days used in calculations) for selected pollutant and meteorological variables by site for the 3-month study period.

Table 3.25 lists the correlations established between values of daily maximum ozone and various meteorological and pollutant variables. In general, the correlations are not very high. The strongest correlations are found with the variables maximum temperature, percent possible sunshine, and solar radiation. This is, of course, a consequence of the necessity for ultraviolet radiation in the photochemical formation of ozone.

The values of maximum ozone do not correlate well with 0500-0800 CST values of $NO_x$ as measured at either the Health Department or Post Office site. Correlations are also poor between ozone maximum values and morning nonmethane hydrocarbon values determined in the city by the automated chromatograph (NMHC) or by summing individual hydrocarbon species (ΣNMHC). The same can be said for correlations with $NO/NO_x$ and the ratio of ΣNMHC to $NO_x$. A good correlation between maximum ozone and the 0500-0800 CST average values mentioned above may not have been expected a priori since trajectory analyses (Appendix A) suggest that the air parcel in the vicinity of the

TABLE 3.24. SUMMARY STATISTICS FOR POLLUTANT AND METEOROLOGICAL VARIABLES BY SITE

| Variable | OCH | WYN | VER | SKI | SPE | HD | PO | LM |
|---|---|---|---|---|---|---|---|---|
| Daily Maximum $O_3$ | | | | | | | | |
| mean, ppm | .072 | .071 | .076 | .068 | .072 | .066 | .055 | .069 |
| s.d. | .019 | .019 | .025 | .018 | .021 | .020 | .022 | .018 |
| max | .114 | .123 | .151 | .120 | .135 | .124 | .127 | .127 |
| no. days | 85 | 86 | 92 | 84 | 87 | 82 | 81 | 92 |
| % days $O_3$>.08 | 30.6 | 26.7 | 38.0 | 26.2 | 33.3 | 18.3 | 12.3 | 26.1 |
| NO (5-8 CST) | | | | | | | | |
| mean, ppm | .001 | .001 | .003 | .000 | .007 | .011 | .036 | .002 |
| s.d. | .002 | .001 | .003 | .000 | .008 | .019 | .039 | .002 |
| max | .006 | .008 | .011 | .002 | .056 | .118 | .170 | .010 |
| no. days | 85 | 87 | 77 | 80 | 84 | 81 | 79 | 88 |
| $NO_2$ (5-8 CST) | | | | | | | | |
| mean, ppm | .006 | .005 | .008 | .005 | .010 | .017 | .028 | .005 |
| s.d. | .002 | .003 | .003 | .003 | .005 | .009 | .010 | .004 |
| max. | .012 | .011 | .015 | .016 | .028 | .043 | .048 | .019 |
| no. days | 85 | 85 | 85 | 88 | 85 | 82 | 79 | 90 |
| $NO_x$ (5-8 CST) | | | | | | | | |
| mean, ppm | .003 | .005 | .011 | .005 | .017 | .028 | .064 | .007 |
| s.d. | .003 | .003 | .005 | .003 | .010 | .026 | .046 | .005 |
| max. | .016 | .012 | .021 | .017 | .065 | .149 | .209 | .021 |
| no. days | 85 | 87 | 84 | 87 | 87 | 83 | 79 | 90 |
| NMHC (5-8 CST) | | | | | | | | |
| mean, ppm | | .530 | | | | .231 | .607 | |
| s.d. | | .503 | | | | .255 | .462 | |
| max. | | 1.760 | | | | 1.190 | 3.110 | |
| no. days | | 25 | | | | 50 | 41 | |
| ΣNMHC (5-8 CST) | | | | | | | | |
| mean, ppm | | | | | | .317 | .538 | .240 |
| s.d. | | | | | | .224 | .448 | .213 |
| max. | | | | | | 1.457 | 3.684 | 1.136 |
| no. days | | | | | | 68 | 71 | 59 |
| Wind Direction (5-17 CST) | | | | | | | | |
| mean, degrees | 156 | 162 | | | | 172 | | 167 |
| s.d. | 71 | 83 | | | | 68 | | 73 |
| no. days | 87 | 81 | | | | 89 | | 82 |

(continued)

TABLE 3.24 (continued)

| Variable | OCH | WYN | VER | SKI | SPE | HD | PO | LM |
|---|---|---|---|---|---|---|---|---|
| | | | | Site | | | | |
| Wind Speed (5-17 CST) | | | | | | | | |
| mean, mph | 4.3 | 6.9 | | | | 8.0 | | 6.1 |
| s.d. | 2.3 | 3.9 | | | | 4.4 | | 3.6 |
| max. | 12.2 | 18.1 | | | | 19.8 | | 16.5 |
| no. days | 72 | 82 | | | | 88 | | 81 |
| Ozone (5-8 CST) | | | | | | | | |
| mean, ppm | .027 | .029 | .022 | .022 | .021 | .020 | .012 | .026 |
| s.d. | .009 | .012 | .013 | .010 | .011 | .011 | .008 | .012 |
| max. | .052 | .059 | .054 | .046 | .068 | .068 | .037 | .051 |
| no. days | 85 | 88 | 85 | 88 | 78 | 78 | 81 | 91 |

## TABLE 3.25. CORRELATIONS BETWEEN DAILY MAXIMUM OZONE AND METEOROLOGICAL AND POLLUTANT VARIABLES BY SITE

| Variable | Site | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | OCH | WYN | VER | SKI | SPE | HD | PO | LM |
| Max. temp. | .55 | .57 | .66 | .44 | .59 | .48 | .26 | .41 |
| % Sun | .47 | .32 | .44 | .34 | .44 | .34 | .17 | .23 |
| Sol. rad. | .46 | .38 | .58 | .30 | .50 | .38 | .23 | .25 |
| Dew pt. | .28 | .28 | .28 | .16 | .32 | .20 | .20 | .13 |
| WS (HD) (a) | -.02 | -.11 | -.06 | -.13 | -.18 | -.29 | -.49 | -.19 |
| WD (HD) (a) | .10 | .10 | .19 | .09 | .09 | .01 | -.12 | -.05 |
| $NO_x$ (HD) (b) | .18 | .23 | -.06 | .17 | .10 | -.03 | .09 | .11 |
| $NO_x$ (PO) | .04 | .18 | .13 | .11 | .01 | -.11 | -.34 | -.01 |
| $NO_x$ (LM) | .39 | .36 | .51 | .24 | .51 | .41 | .36 | .32 |
| NMHC (HD) | .29 | .19 | .03 | .29 | .21 | .11 | .20 | .14 |
| NMHC (PO) | .33 | .40 | -.03 | .37 | .37 | .02 | .10 | .20 |
| $\Sigma$NMHC (HD) | .20 | .19 | -.02 | .15 | .19 | .05 | .09 | .22 |
| $\Sigma$NMHC (PO) | .35 | .42 | .10 | .37 | .34 | .06 | .08 | .28 |
| $\Sigma$NMHC (LM) | .35 | .37 | .24 | .31 | .52 | .32 | .39 | .31 |
| $NO_2/NO_x$ (HD) | .05 | .06 | .31 | .07 | .14 | .17 | .04 | .13 |
| $NO_2/NO_x$ (PO) | .07 | -.02 | .08 | .00 | .09 | .25 | .44 | .10 |
| $NO_2/NO_x$ (LM) | -.03 | -.20 | -.08 | -.11 | -.07 | -.03 | -.05 | -.12 |
| $NMHC/NO_x$ (HD) | -.05 | -.09 | -.02 | .13 | -.03 | .16 | -.03 | .04 |
| $NMHC/NO_x$ (PO) | .15 | -.01 | -.15 | .05 | .20 | .13 | .33 | .20 |
| $\Sigma NMHC/NO_x$ (HD) | -.01 | -.04 | .02 | -.09 | -.01 | .02 | -.12 | .05 |
| $\Sigma NMHC/NO_x$ (PO) | .23 | .15 | .03 | .21 | .22 | .13 | .28 | .30 |
| $\Sigma NMHC/NO_x$ (LM) | -.05 | -.01 | -.13 | -.04 | .11 | .06 | .20 | .04 |
| Ave. sample size (days) meteoro. | 85 | 84 | 90 | 80 | 85 | 80 | 80 | 90 |
| Ave. sample size (days) pollutants | 80 | 75 | 80 | 75 | 80 | 75 | 75 | 80 |
| NMHC sample size (days) | 45 | 45 | 45 | 40 | 45 | 45 | 45 | 45 |

(a) Vector average for the hours 0500-1700 CST. (b) All pollutants averaged from 0500 to 0800 CST.

maximum ozone site at the time of maximum ozone was upwind of Tulsa during the period of morning precursor emissions. Mesoscale trajectories show that, more often, the air parcel present at the northern site at the time of ozone maxima passed across the city between the hours of 0900 and 1200 CST and not during the 0500 to 0800 CST period.

Stepwise regressions were also performed. This procedure is commonly used to indicate which variables out of a large group appear to be the most important in predicting a given variable (e.g., maximum ozone). The procedure assumes that a linear relationship exists between the dependent variable and the independent variable. Table 3.26 lists the results of stepwise regressions with daily maximum ozone as the dependent variable. For example, at the Sperry site, the most important independent variable in predicting maximum ozone is maximum temperature; second in importance is wind speed; third, ΣNMHC; and fourth, $NO_x$. Maximum temperature (a variable closely associated with percent sunshine) is the most important variable in predicting maximum ozone at seven out of eight sites. Anywhere from 38 to 56 percent of the variation in ozone concentration was explained by the independent variables checked in the table.

Table 3.27 is similar to the previous table except that the data were stratified to include only those days having mean wind direction between 116° and 231° as measured at the Health Department site between the hours of 0500 and 1700 CST. In general, the results of the stepwise regression are similar to those obtained with the nonstratified data base; maximum temperature ranks first in explaining ozone variation at six of the eight sites. In contrast to the nonstratified data, variations in ozone at the Post Office and Health Department sites show an increased dependence on $NO_2/NO_x$, and ΣNMHC (each as measured at the Post Office site) and the meteorological variables wind speed, maximum temperature, and solar radiation as measured at the Health Department, Tulsa International Airport, and Skiatook, respectively.

Finally, the means of several pollutant and meteorological variables were calculated for three levels of maximum ozone. The levels chosen were: low (less than 0.06 ppm); medium (between 0.06 and 0.08 ppm); high (greater than 0.08 ppm). Table 3.28 is a compilation of the 0500-0800 CST average

TABLE 3.26. RESULTS OF STEPWISE REGRESSIONS BY STATION WITH DAILY MAXIMUM OZONE AS THE DEPENDENT VARIABLE

| Independent Variable | Station | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Mounds | Post Office | Health Dept. | Sperry | Skiatook | Vera | Wynona | Ochelata |
| Max. Temperature | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| Percent Sun | | | | | | | | |
| Solar Radiation | | | | | | | | |
| Dew Point | | | 4 | | 4 | | | |
| Wind Speed (a) | 3 | 1 | 2 | 2 | | | 3 | |
| Wind Direction (a) | | | | | | 3 | | |
| NOx (b) | | | | 4 | | | | 3 |
| $NO_2$/NOx (b) | | 3 | 3 | | 3 | 2 | | |
| ΣNMHC (b) | | | | 3 | 2 | | 2 | 2 |
| ΣNMHC/NOx (b) | 2 | | | | | | | |
| Number of days | 65 | 65 | 62 | 64 | 62 | 65 | 63 | 65 |
| $R^2$ = $(corr)^2$ | .38 | .53 | .52 | .53 | .43 | .56 | .55 | .44 |
| R = corr | .62 | .73 | .72 | .73 | .66 | .75 | .74 | .66 |

(a) At the Health Department site (mean value between the hours 0500 and 1700 CST).

(b) At the Post Office site during 0600 to 0900 CDT.

TABLE 3.27. RESULTS OF STEPWISE REGRESSIONS BY STATION WITH DAILY MAXIMUM OZONE AS THE DEPENDENT VARIABLE WITH WIND DIRECTIONS GREATER THAN 116°, LESS THAN 231° AT POST OFFICE

| Independent Variable | Station | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Mounds | Post Office | Health Dept. | Sperry | Skiatook | Vera | Wynona | Ochelata |
| Max. Temperature | 1 | | 3 | 1 | 1 | 1 | 1 | 1 |
| Percent Sun | | 3 | | | | | | |
| Solar Radiation | | | | | | | | |
| Dew Point | | | 5 | | 3 | 4 | 4 | |
| Wind Speed (a) | | 2 | 2 | 2 | 4 | 3 | 2 | 2 |
| Wind Direction (a) | | 4 | 1 | | | | | |
| NOx (b) | | | | | 5 | | 5 | |
| $NO_2/NO_x$ (b) | | 1 | 4 | 3 | | 2 | | |
| ΣNMHC (b) | | | | 4 | 2 | | 3 | |
| $\Sigma NMHC/NO_x$ (b) | 2 | | | | | | | 3 |
| Number of days | 47 | 47 | 45 | 46 | 44 | 47 | 45 | 47 |
| $R^2 = (corr)^2$ | .25 | .53 | .53 | .53 | .47 | .58 | .55 | .35 |
| R = corr | .50 | .73 | .73 | .73 | .69 | .76 | .74 | .59 |

(a) At the Health Department site.

(b) At the Post Office site during 0600 to 0900 CDT.

TABLE 3.28. AVERAGES OF METEOROLOGICAL AND POLLUTANT VARIABLES FOR DIFFERENT LEVELS OF DAILY MAXIMUM OZONE BY STATION

| | Maximum Pollutant Variables | | | | Meteorological Variables | | |
|---|---|---|---|---|---|---|---|
| Station | Ozone levels | $NO_x$ (ppm) | $NO_2/NO_x$ | ΣNMHC ppmC | Wind speed (a) | Max. temp. (Airport) | Solar radiation (Skiatook) |
| Liberty Mounds | <.06 | .062 | .53 | .378 | 8.4 | 84.2 | 376 |
| | intermed. | .071 | .55 | .526 | 8.7 | 91.6 | 516 |
| | >.08 | .057 | .63 | .741 | 6.2 | 92.9 | 513 |
| Post Office | <.06 | .076 | .50 | .545 | 9.6 | 88.1 | 442 |
| | intermed. | .048 | .64 | .508 | 6.0 | 89.5 | 450 |
| | >.08 | .048 | .73 | .584 | 4.5 | 95.4 | 584 |
| Health Department | <.06 | .067 | .51 | .547 | 8.6 | 85.6 | 406 |
| | intermed. | .069 | .57 | .557 | 8.1 | 92.2 | 519 |
| | >.08 | .045 | .65 | .516 | 4.8 | 93.2 | 527 |
| Sperry | <.06 | .054 | .57 | .397 | 7.9 | 82.4 | 333 |
| | intermed. | .079 | .51 | .554 | 9.3 | 91.8 | 524 |
| | >.08 | .060 | .59 | .696 | 6.5 | 94.7 | 563 |
| Skiatook Lake | <.06 | .050 | .59 | .382 | 8.2 | 85.6 | 393 |
| | intermed. | .069 | .54 | .585 | 8.1 | 90.6 | 480 |
| | >.08 | .060 | .62 | .726 | 6.7 | 92.9 | 536 |
| Vera | <.06 | .052 | .57 | .420 | 7.4 | 82.8 | 317 |
| | intermed. | .071 | .51 | .715 | 9.5 | 91.0 | 512 |
| | >.08 | .070 | .60 | .537 | 7.6 | 95.2 | 586 |
| Wynona | <.06 | .049 | .58 | .338 | 7.2 | 83.0 | 374 |
| | intermed. | .071 | .55 | .507 | 8.9 | 89.2 | 451 |
| | >.08 | .069 | .55 | .787 | 6.3 | 95.1 | 558 |
| Ochelata | <.06 | .048 | .59 | .380 | 6.9 | 81.8 | 323 |
| | intermed. | .083 | .50 | .573 | 9.0 | 92.5 | 523 |
| | >.08 | .058 | .62 | .687 | 7.4 | 92.8 | 537 |
| No. of times variable increased from low to high level of max. ozone | | 5 | 7 | 8 | 2 | 8 | 8 |
| No. of times variable decreased from low to high level of max. ozone | | 3 | 1 | 0 | 6 | 0 | 0 |

(a) Speed in mph as measured at Health Department, 0500-1700 average.

values of pollutant variables $NO_x$, $NO_2/NO_x$, and ΣNMHC as measured at the Post Office site and the meteorological variables wind speed, maximum temperature, and the sum of hourly solar radiation values for the day as measured at the Health Department, Tulsa International Airport, and Skiatook, respectively. The data show increasing levels of ozone with increasing temperature and solar radiation and generally higher values of ozone with lower wind speeds.

## 3.5 ANALYSIS AND INTERPRETATION OF THE HYDROCARBON DATA BASE

### 3.5.1 Background

One objective of the Tulsa field monitoring program was acquisition of a nonmethane hydrocarbon data base for sites upwind of and in the city, especially for the hours 0500 to 0800 CST (0600 to 0900 CDT), a time frame important to EPA modeling and control strategy efforts. This data base was compiled using two methods. One method was to collect hydrocarbon samples, analyze each sample for 47 individual hydrocarbon species, and sum the concentrations. Such samples were collected in an integrated fashion by filling stainless steel containers with air from the station sample manifold over a 3-hour period. Details of the sampling and gas chromatography analysis procedures and quality assurance experiments are given in Volume I of this report; concentrations and sums of individual hydrocarbon species are listed in Volume II. Samples were collected during hours 0500 to 0800 CST each day of the study at the southern site, Liberty Mounds, which was generally upwind of Tulsa, and at the Post Office and Health Department city sites. During the period of aircraft flights (August 26 through September 17), additional ground samples were collected at all sites in the system during the hours 0800 to 1100 CST or 1300 to 1600 CST. Hydrocarbon samples were also collected by the aircraft during vertical spirals upwind of, over, and downwind of the city and during low passes over the Tulsa International and Downtown Airport runways. Table 3.29 summarizes the number of hydrocarbon samples collected at each site or location.

The second approach to measurement of nonmethane hydrocarbons was through the use of the Beckman Model 6800 automated chromatograph. This monitor was in operation at the Health Department site from July 28 through

TABLE 3.29. NUMBER OF HYDROCARBON SAMPLES COLLECTED IN TULSA

| Site or location | Morning 05 to 08 CST | Midmorning 08 to 11 CST | Afternoon 13 to 16 CST |
|---|---|---|---|
| Liberty Mounds | 70 | 7 | 0 |
| Health Department | 77 | 7 | 1 |
| Post Office | 78 | 7 | 1 |
| Sperry | 10 | 7 | 5 |
| Skiatook Lake | 0 | 0 | 6 |
| Vera | 0 | 0 | 6 |
| Wynona | 0 | 0 | 5 |
| Ochelata | 0 | 0 | 5 |
| Aircraft, upwind | 24 | 0 | 0 |
| Aircraft, over city | 10 | 0 | 0 |
| Aircraft, low pass | 11 | 0 | 0 |
| Aircraft, downwind | 0 | 0 | 12 |

September 20, at the Post Office site from July 28 through August 26, and at the Wynona site from August 29 through September 22. Mean monthly diurnal curves of hourly concentrations of total hydrocarbon, methane, and, by difference, nonmethane hydrocarbons are presented in Volume I. Hourly values are listed in Volume II.

In addition to the above samples, five Tenax adsorption cartridges were collected and analyzed for organic components by gas chromatography/mass spectrometry. These analyses were qualitative in nature and served several purposes: to confirm the presence or absence of specific hydrocarbons and other compounds; to establish the relative order of chromatographic elution of hydrocarbons; and to quantitatively compare, on a relative basis, the variation in organic compound content of samples collected upwind of, in, and downwind of the city of Tulsa.

In this section, comparisons will be made among the measurements of nonmethane hydrocarbon concentrations (determined by summing individual species) at the sites in Tulsa as well as in other cities. Concentrations of selected hydrocarbons and sums of hydrocarbons from Tulsa ground and aircraft samples will also be interpreted with respect to site location, day of the week, time of day, distance of the sampling site from Tulsa, altitude, and influences of sources and meteorological conditions. From this, the average concentration levels of hydrocarbons contained in background air, in air over the urban area, and in air downwind of the city can be established. The contribution of various sources can also be assessed.

A quantitative comparison will be made between NMHC as the sum of individual hydrocarbons and NMHC as given by the automated chromatograph. A qualitative comparison will also be made between the hydrocarbon species measurements and the results of the gas chromatography/mass spectrometry studies.

### 3.5.2 Comparison of Nonmethane Hydrocarbons at Various Sites

Values of nonmethane hydrocarbons (obtained by summing values of individual species) are shown in Figure 3.5 for morning samples at three Tulsa locations, two St. Louis locations, and one location in Ohio. The St. Louis and Ohio distributions are based on data reported by Lonneman.(9) Listed on the figure are (1) the date and location of the samples and (2) the average percentage of nonmethane hydrocarbon attributed to vehicular tailpipe emissions. This was determined by considering acetylene as an indicator of tailpipe NMHC emissions. An acetylene factor of 15.5 was used in making these computations. This factor (15.5) is based on experimental work by Kopczynski et al.(10) and Lonneman(11) in which the total hydrocarbon content of vehicular emissions in tunnel samples is compared to the acetylene content of the same sample. In Kopczynski's work, the percentage calculation involves the ratio of estimated vehicular emissions (acetylene concentration × 15.5) to the observed total nonmethane hydrocarbon concentration.

The distribution of NMHC concentrations at the generally upwind site, Liberty Mounds, has a median value around 150 ppbC, a value somewhat higher than that found for the Wilmington, Ohio, site. Wilmington is located in the Ohio Valley and is within 80 km (50 mi) of the large cities of Cincinnati, Dayton, and Columbus. The nearest major metropolitan area in the predominant upwind direction from Liberty Mounds is Dallas-Fort Worth, approximately 400 km (250 mi) away. The average percentage of NMHC attributed to vehicular exhaust was considerably lower in the Liberty Mounds samples than it was in the Wilmington samples. Thus, it seems that the hydrocarbon constituents of the air to the south of Tulsa are, in large part, derived from sources other

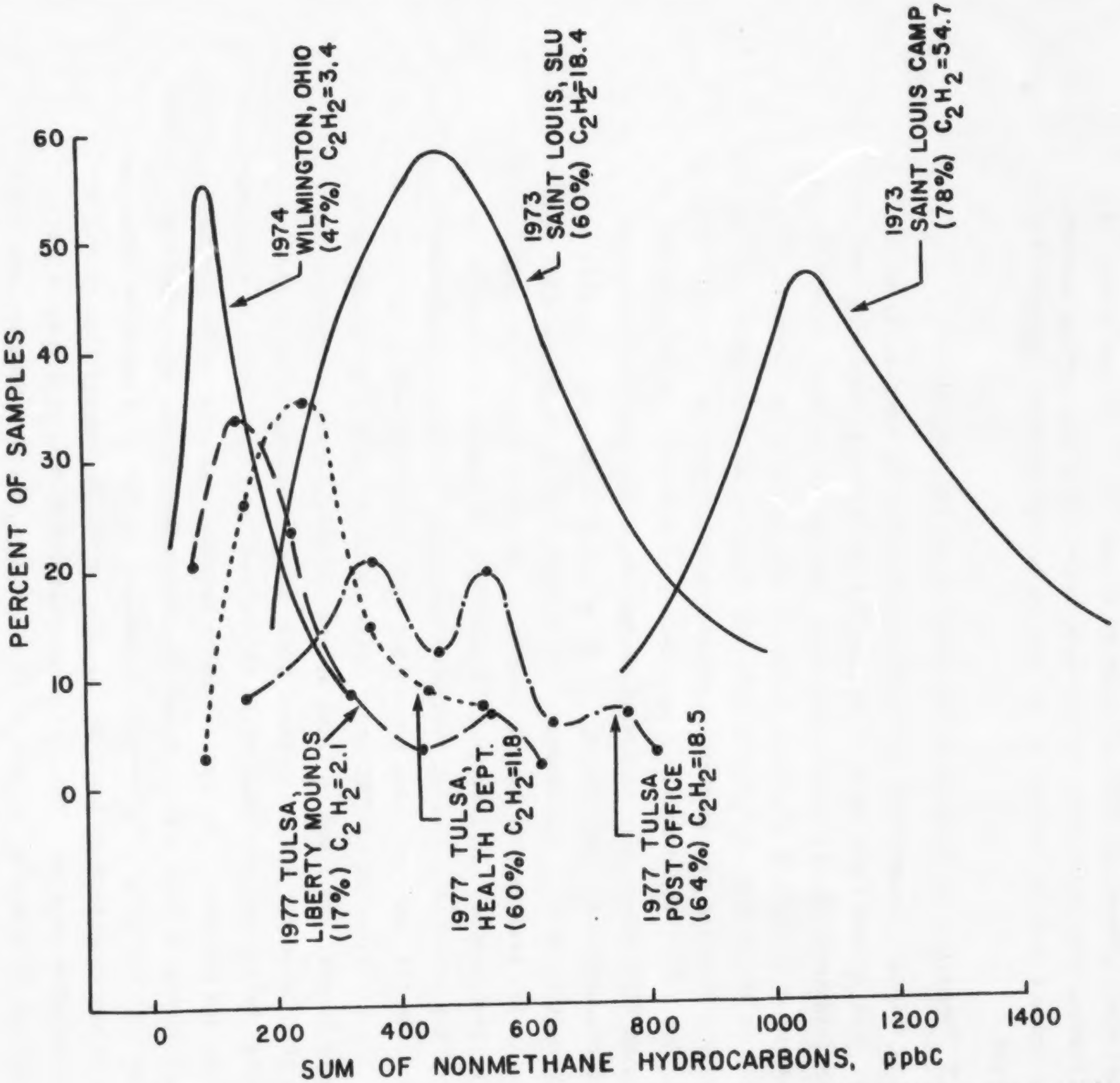


Figure 3.5. Frequency distribution of nonmethane hydrocarbon concentrations.

than vehicular emissions. In fact, on the average, 74 percent of NMHC at Liberty Mounds is due to alkanes; only 64.3 percent is due to alkanes at the downtown Post Office site. This is not surprising since the area south of Tulsa is dotted with oil fields, natural gas sites, and petrochemical production and storage facilities. The nearest such source south of Liberty is a small refinery ot Okmulgee, approximately 27 km (17 mi) away.

Liberty Mounds also recorded several cases in which the sum of NMHC exceeded 500 ppbC. On these days, the winds during the hours preceding the sample were either calm or from the north. The occurrence of higher than average concentrations of low molecular weight hydrocarbons was noted on these same days. This suggests that emissions associated with the refinery complex in Tulsa may have influenced NMHC levels as far south as Liberty Mounds.

Early morning samples from the Health Department site gave a NMHC distribution having a median around 250 ppbC. On the average, the acetylene concentration was 11.8 ppbC and 60 percent of the hydrocarbon burden was attributable to vehicular emissions. This percentage is similar to Kopczynski's findings in St. Louis at the Saint Louis University site(10).

The frequency distribution of morning NMHC concentrations at the Post Office site is bimodal whereas the Health Department, Wilmington, and St. Louis data show single peak distributions. Two distinct humps are observed; one is centered around 350 ppbC, the other at about 550 ppbC.

### 3.5.3 Comparison of Classes of Hydrocarbons

Table 3.30 summarizes by month and for the entire period the average values of the alkene, alkane, and aromatic classes of hydrocarbons for morning samples collected at three surface sites.

The generally upwind site, Liberty Mounds, was lowest of the three sites in average concentration for the alkene (olefin) class for every month. The inner city site, the Post Office, had average alkene concentrations almost three times higher than those of the background site (ten times higher if the ethylene concentration, which may have been enhanced by exhaust from the chemiluminescent ozone monitor, is included). Concentrations at the Health Department site were about twice as high as those at Liberty

Mounds. The average sum of alkanes (paraffins) at the background site was not greatly different from that of the Health Department site. At the Post Office site, average alkane, aromatic, and nonmethane hydrocarbon concentrations were significantly higher than at the other two sites.

The percentage of nonmethane hydrocarbons due to vehicular tailpipe emissions was computed for each sample; averages are given in Table 3.30. Liberty Mounds was lowest, with an average of only 17 percent. The Health Department and Post Office sites averaged 60 and 64 percent, respectively. These percentages represent a maximum value because they were calculated based on an acetylene factor of 15.5, which was itself derived by Kopczynski and Lonneman from automobile tunnel samples assumed to be composed 100 percent of vehicular emissions. In Kopczynski's work(10), a greater number of hydrocarbons were identified than is the case in the present study. Thus the concentration of NMHC would have been greater had additional compounds been analyzed, and the percentage attributed to vehicular exhaust would have been correspondingly less.

### 3.5.4 Comparison of Individual Hydrocarbon Compounds

The concentrations of individual hydrocarbons, as expected, show differences between background and city sites as did the sums of hydrocarbons. Table 3.31 lists average values for six alkenes and acetylene. In most cases, the concentration of an individual compound was lowest at the background site, Liberty Mounds, and highest at the downtown Post Office site. Note that no detectable quantities of the naturally emitted compound, β-pinene, were measured at any of the monitoring stations. α-pinene eluted from the chromatographic column at the same time as p-xylene, and thus was not quantified separately. It is likely, however, that the concentration of α-pinene was very low. Another naturally occurring compound, isoprene, was sought in the analysis, but was found to elute at the same time as trans-2-pentene. The average concentration of trans-2-pentene plus isoprene was higher in the city samples than in background samples, suggesting that, if isoprene is truly present, its source is associated with the urban area emissions. At any rate, the average concentration of trans-2-pentene plus isoprene was quite low and would not be expected to exert a significant influence on the ozone production potential of this area.

TABLE 3.30. AVERAGE SUM OF HYDROCARBON CLASSES AT TULSA SITES FOR MORNING SAMPLES; VALUES IN ppbC.

| | Liberty Mounds | | | | Health Department | | | | Post Office | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | JUL | AUG | SEPT | ALL | JUL | AUG | SEPT | ALL | JUL | AUG | SEPT | ALL |
| Average Sum Alkenes | 8.5 | 6.7 | 4.1 | 5.7 | 33.4 | 31.3 | 28.6 | 30.7 | 50.1 | 67.9 | 56.3 | 59.9 |
| Average Sum Alkanes | 176.7 | 175.7 | 170.2 | 173.4 | 162.3 | 281.8 | 180.5 | 215.4 | 298.7 | 451.6 | 286.0 | 357.9 |
| Average Sum Aromatics | 91.4 | 44.8 | 29.6 | 46.8 | 52.1 | 84.1 | 44.9 | 61.6 | 67.1 | 126.7 | 73.4 | 92.2 |
| Average Sum NMHC | 247.7 | 230.8 | 209.3 | 228.0 | 256.6 | 407.1 | 268.5 | 316.7 | 430.1 | 681.5 | 436.9 | 534.0 |
| Average Percent NMHC Due to Tailpipe Emissions (a) | 11 | 15 | 20 | 17 | 52 | 49 | 75 | 60 | 40 | 68 | 73 | 64 |

(a) Calculated using an acetylene factor of 15.5.

TABLE 3.31. AVERAGE VALUES, ppbC, FOR ALKENES AND ALKYNES IN MORNING HYDROCARBON SAMPLES

| | Liberty Mounds | Health Department | Post Office |
|---|---|---|---|
| Ethylene | (a) | 22.2 | 45.0 |
| Propylene | 4.2 | 7.3 | 10.7 |
| t-2-Pentene + Isoprene | 1.6 | 2.3 | 3.4 |
| 1-Hexene | 0.2 | 0.1 | 0.6 |
| β-Pinene | 0.0 | 0.0 | 0.0 |
| Acetylene | 2.1 | 11.8 | 18.5 |

(a) Ethylene values at Liberty Mounds were invalidated due to suspected contamination from the chemiluminescent ozone monitor.

Table 3.32 lists average values for hydrocarbons classed as alkanes. This table shows a tendency toward higher concentrations of low molecular weight alkanes, and quite small or zero concentrations of long-chain hydrocarbons such as nonane, decane, undecane, and dodecane. For most alkanes, the concentrations are higher at the city sites than at the background site. However, the Liberty Mounds samples are, on the average, higher in ethane, propane, and isobutane than the Post Office site and almost as high in n-butane. This distribution may perhaps be explained as a combination of two factors that affected the Liberty Mounds site. First, on those few days when winds were from the north during the predawn hours, concentrations of low molecular weight alkanes were elevated; these days are included in the average. Second, there was a small refinery near the city of Okmulgee, which is 27 km (17 mi) south of the site, and it may have been a source of these compounds.

The average morning concentration of almost every alkane in the Post Office samples was higher than at either of the other sites. It was thought that measurements made at this site might be influenced by the nearby petrochemical refinery complex, which is located about 3 to 5 km south and west of the Post Office at a direction of 172° to 269°. To investigate this possibility, samples at the Post Office site were stratified based on average wind direction for the hours 0400, 0500, and 0600 as measured at the Tulsa International Airport. Table 3.33 shows that 20 of 76 days had average wind directions from 172° to 269°. Average concentration values for propane, isobutane, and butane (each associated with refinery operations or gasoline storage) are statistically significantly different (based on the t-test) than are average concentrations on days when winds are from other directions. The percentage of NMHC due to propane (or butane) is also higher when winds are from 172° to 269° (refer to Table 3.33). The difference in the average concentrations of isopentane is not as great as for propane, isobutane, or butane when stratified days are compared and is not statistically significantly different. This might be expected since isopentane is less volatile and fewer losses from refinery operations would be expected. Furthermore, isopentane is associated with vehicular tailpipe emissions and gasoline evaporation. Note that the average concentration of acetylene, a key indi-

TABLE 3.32. AVERAGE VALUES, ppbC, FOR ALKANES IN MORNING HYDROCARBON SAMPLES

| Alkane | Liberty Mounds | Health Department | Post Office |
|---|---|---|---|
| Ethane | 36.4 | 26.5 | 39.8 |
| Propane | 54.9 | 23.1 | 38.9 |
| Isobutane | 11.4 | 10.9 | 24.8 |
| n-Butane | 25.7 | 26.6 | 69.3 |
| Isopentane | 17.4 | 31.3 | 58.8 |
| n-Pentane + Cyclopentane | 36.3 | 39.1 | 41.5 |
| 2,2-Dimethylbutane | 0.0 | 0.1 | 0.2 |
| 2-Methylpentane | 4.0 | 8.5 | 11.6 |
| 3-Methylpentane | 9.1 | 17.7 | 17.7 |
| n-Hexane | 3.1 | 5.5 | 10.4 |
| 2,4-Dimethylpentane | 0.4 | 0.6 | 1.1 |
| 2-Methylhexane | 1.5 | 5.7 | 7.9 |
| 3-Methylhexane | 1.0 | 4.4 | 4.6 |
| 2,2,4-Trimethylpentane | 1.7 | 4.8 | 8.3 |
| n-Heptane | 0.7 | 3.1 | 5.1 |
| Methylcyclohexane | 0.5 | 2.1 | 1.6 |
| 2,3,4-Trimethylpentane | 0.3 | 0.3 | 0.8 |
| 2-Methylheptane | 2.6 | 8.9 | 13.8 |
| 3-Methylheptane | 0.4 | 1.1 | 2.7 |
| n-Octane | 0.5 | 2.0 | 2.8 |
| n-Nonane | 0.2 | 0.3 | 1.2 |
| n-Decane | 0.0 | 0.0 | 0.2 |
| n-Undecane | 0.0 | 0.0 | 0.0 |
| n-Dodecane | 0.0 | 0.0 | 0.0 |

cator of vehicular exhaust, is actually lower when winds are from the direction of the refinery as compared to other directions.

Six days during the summer had light and variable winds during the hours just preceding the hydrocarbon sample and were classed as calm. On these days, the average concentrations of low molecular weight compounds were much higher than on other measurement days at the Post Office site.

Average morning concentration values for aromatic compounds are given in Table 3.34. Generally, concentrations of aromatics are higher at the city sites than at the background site. Benzene concentrations seem to be quite high, even when compared to values found at one site in the Houston area in 1976(12), where the aromatic portion of NMHC was often predominant. The average concentration given for benzene may not be reliable because the benzene peak eluted near the beginning of the chromatograph in a crowded region and some of the samples may have suffered interferences from nearby compounds or baseline effects not compensated for by the computerized data acquisition system.

TABLE 3.33. AVERAGE 0600 TO 0900 CDT HYDROCARBON CONCENTRATIONS BY WIND DIRECTION. TULSA POST OFFICE SITE

| Average Wind Direction for Hours 04, 05, and 06 at Airport (Number of Cases) | Propane (ppbC)* | Acetylene (ppbC) | Isobutane (ppbC) | Butane (ppbC)* | Isopentane (ppbC) |
|---|---|---|---|---|---|
| 270°-90°(20) | 30.6 (7.0) | 21.4 | 15.2 | 39.6 (8.9) | 43.3 |
| 91°-171°(30) | 30.2 (6.3) | 15.7 | 19.5 | 53.4 (10.3) | 50.0 |
| 270°-171°(50) | 30.4 (6.6) | 18.0 | 17.8 | 47.8 (9.7) | 47.3 |
| 172°-269°(20) | 46.8 (8.7) | 13.8 | 28.6 | 79.8 (13.8) | 56.4 |
| Calm (06) | 65.2 (6.4) | 32.8 | 68.6 | 204.0 (11.8) | 158.1 |

*Average percentage of sum of NMHC in parentheses.

TABLE 3.34. AVERAGE VALUES, ppbC, FOR AROMATICS IN MORNING HYDROCARBON SAMPLES

| | Liberty Mounds | Health Department | Post Office |
|---|---|---|---|
| Benzene | 15.3 | 23.8 | 29.6 |
| Toluene | 7.3 | 9.5 | 13.8 |
| Ethylbenzene | 3.4 | 5.9 | 3.9 |
| p-Xylene | 0.8 | 0.9 | 2.0 |
| m-Xylene | 1.4 | 2.4 | 4.7 |
| o-Xylene | 0.8 | 1.7 | 2.9 |
| n-Propylbenzene | 3.1 | 2.1 | 2.9 |
| m-Ethyltoluene | 1.0 | 0.7 | 1.7 |
| 1,3,5-Trimethylbenzene | 1.0 | 0.6 | 1.8 |
| t-Butylbenzene | 0.8 | 0.1 | 1.0 |
| o-Ethyltoluene | 0.8 | 0.3 | 1.0 |
| 1,2,4-Trimethylbenzene | 9.4 | 11.0 | 18.5 |
| 1,2,3-Trimethylbenzene | 1.0 | 1.0 | 3.4 |
| n-Butylbenzene | 0.9 | 1.9 | 5.0 |

### 3.5.5 Variation in Hydrocarbon Content by Day of the Week

Samples of nonmethane hydrocarbons taken in a city between the hours of 0500 and 0800 CST (0600 and 0900 CDT) would be expected to show a distinct variation in constituent composition with the day of the week. Acetylene, a key indicator of vehicular emissions, would be expected to be higher during the workdays Monday through Friday and lower on the weekend when traffic patterns differ. Table 3.35 illustrates the variation in acetylene concentration by day of the week at the southern site, Liberty Mounds, and the two city sites. The two city sites show a strong weekday/weekend variation; the southern site, shows no pattern of variation.

TABLE 3.35. AVERAGE ACETYLENE CONCENTRATIONS BY DAY OF THE WEEK

| Site | No. of Samples | Acetylene, ppbC | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Mon. | Tue. | Wed. | Thur. | Fri. | Sat. | Sun. |
| Post Office | 78 | 25.3 | 22.8 | 16.7 | 22.4 | 21.0 | 11.2 | 9.5 |
| Health Department | 77 | 18.6 | 14.1 | 9.5 | 14.6 | 13.6 | 7.2 | 4.0 |
| Liberty Mounds | 70 | 1.8 | 2.1 | 1.7 | 2.5 | 2.4 | 2.7 | 1.5 |

### 3.5.6 Hydrocarbon Content of Samples Taken During Aircraft Low-Pass Operations

Table 3.36 summarizes the results of hydrocarbon grab samples collected during the aircraft morning low-pass operation at the Downtown Airport. Refer to Figure 1.1 for the location of this airport. Table 3.37 is a summary of hydrocarbon data for the 0500 to 0800 CST period at the downtown Post Office site on the same days. The aircraft grab samples were taken over a brief time span (about 1 minute) as the plane passed low over the runway. The Post Office samples were collected over a 3-hour period. However, both samples were taken during the 0500 to 0800 time frame.

Tailpipe emissions (as judged by acetylene concentrations) are common to both sets of data. As expected, the samples taken at the Downtown Airport were lower in acetylene than those at the urban core site because the Post Office (CBD) site is in the vicinity of direct vehicular emissions. Of particular interest are the airport samples for September 2 and 3, which were much higher in NMHC than those of the Post Office. Examination of the individual hydrocarbon data reveals that the major contributors to the airport totals were the low molecular weight alkanes, especially propane, butane, and isopentane. Samples taken at the Post Office site were not nearly so rich in these compounds and had higher values of acetylene. Thus it seems that sources other than vehicular emissions were responsible for the elevated values at the Downtown Airport. The petrochemical refinery complex lies about 8 km to the south of the airport. Wind directions during the hour preceding the sample on September 2 and 3 were from 170°, a direction which may allow the refinery to directly affect the Downtown Airport and yet only marginally affect the Post Office to the northeast. The high levels may also be partially due to the fact that wind speeds during the hours preceding the sample were low, reducing the dispersion of hydrocarbons prior to their transit northward.

Table 3.38 lists values for selected hydrocarbons and sums for samples collected by the aircraft during low passes over the Tulsa International Airport runway about 1 hour after the low pass at the Downtown Airport. The most significant features of these samples, as compared to those at the Downtown Airport, are the presence of much lower concentrations of hydrocarbons, especially alkanes such as propane, n-butane, and isopentane; and

TABLE 3.36. AIRCRAFT HYDROCARBONS, ppbC; LOW PASS AT DOWNTOWN AIRPORT

| | 8-26<br>Friday<br>0809 CST | 9-02<br>Friday<br>0817 CST | 9-03<br>Saturday<br>0757 CST | 9-16<br>Friday<br>0715 CST | 9-17<br>Saturday<br>0754 CST |
|---|---|---|---|---|---|
| Ethylene | 6.0 | 28.8 | 24.4 | 21.8 | 5.0 |
| Propane | 59.1 | 256.5 | 90.9 | 69.3 | 45.9 |
| Acetylene | 2.0 | 19.6 | 10.4 | 28.0 | 1.4 |
| n-Butane | 92.3 | 536.8 | 236.0 | 88.0 | 75.6 |
| Propylene | 9.9 | 33.9 | 30.6 | 15.3 | 7.2 |
| Isopentane | 67.5 | 333.5 | 177.0 | 65.0 | 48.5 |
| Toluene | 8.4 | 59.7 | 74.9 | 14.7 | 6.9 |
| m-Xylene | 1.4 | 8.6 | 14.0 | 5.0 | 1.1 |
| Sum Alkenes | 20.7 | 78.9 | 72.4 | 39.1 | 13.8 |
| Sum Alkanes | 436.1 | 2124.3 | 1071.9 | 527.2 | 333.2 |
| Sum Aromatics | 62.9 | 219.8 | 192.1 | 61.2 | 41.5 |
| Sum NMHC | 521.7 | 2442.6 | 1346.8 | 655.5 | 389.9 |
| Percent Tailpipe Emissions | 6 | 12 | 12 | 66 | 6 |
| Airport Wind Direction (a) | 180° | 170° | 170° | 180° | 180° |
| Wind Speed, mph(a) | 19.6 | 6.9 | 9.2 | 3.5 | 17.3 |

(a) For the 1-hour period preceding the sample.

TABLE 3.37. POST OFFICE SITE 0500-0800 CST HYDROCARBONS, ppbC; ON DAYS OF DOWNTOWN AIRPORT SAMPLES

| | 8-26 Friday | 9-02 Friday | 9-03 Saturday | 9-16 Friday | 9-17 Saturday |
|---|---|---|---|---|---|
| Ethylene | 48.2 | 62.2 | 37.4 | 59.0 | 33.6 |
| Propane | 40.5 | 50.7 | 20.4 | 54.0 | 21.3 |
| Acetylene | 29.2 | 30.0 | 12.0 | 45.4 | 7.6 |
| n-Butane | 53.2 | 60.4 | 40.0 | 112.0 | 21.2 |
| Propylene | 6.9 | 14.4 | 6.3 | 18.9 | 3.0 |
| Isopentane | 47.0 | 70.0 | 47.0 | 111.5 | 18.5 |
| Toluene | 4.9 | 13.3 | 15.1 | 21.0 | 4.2 |
| m-Xylene | 3.7 | 9.6 | 5.6 | 9.6 | 1.3 |
| Sum Alkenes | 57.3 | 79.8 | 51.0 | 85.3 | 46.4 |
| Sum Alkanes | 312.2 | 419.6 | 230.4 | 638.9 | 204.3 |
| Sum Aromatics | 166.2 | 110.7 | 73.5 | 100.9 | 57.7 |
| Sum NMHC | 564.9 | 640.1 | 366.9 | 870.5 | 314.8 |
| Percent Tailpipe Emissions | 80 | 73 | 51 | 81 | 37 |
| Airport Wind Direction(a) | 173° | 170° | calm[b] | 170° | 167° |
| Wind Speed, mph(a) | 13.8 | 3.5 | 1.2 | 3.1 | 12.7 |

(a) Average for hours 0400, 0500, and 0600.

(b) Calm for two of three hours.

TABLE 3.38. AIRCRAFT HYDROCARBONS, ppbC; LOW PASS AT TULSA INTERNATIONAL AIRPORT

|  | 8-26<br>Friday<br>0903 CST | 9-02<br>Friday<br>0912 CST | 9-03<br>Saturday<br>0901 CST | 9-16<br>Friday<br>0819 CST | 9-17<br>Saturday<br>0857 CST |
|---|---|---|---|---|---|
| Ethylene | 6.4 | 35.6 | 27.1 | 40.0 | 7.8 |
| Propane | 16.8 | 34.5 | 8.7 | 40.5 | 16.5 |
| Acetylene | 3.2 | 31.6 | 10.4 | 40.8 | 3.8 |
| n-Butane | 15.6 | 51.2 | 14.8 | 68.8 | 15.2 |
| Propylene | 3.9 | 17.7 | 2.9 | 20.7 | 6.0 |
| Isopentane | 13.5 | 58.5 | 33.3 | 75.0 | 9.5 |
| Toluene | 4.2 | 29.4 | 15.4 | 28.7 | 3.3 |
| m-Xylene | 0.1 | 9.2 | 3.7 | 10.1 | 1.0 |
| Sum Alkenes | 11.6 | 54.5 | 36.1 | 62.4 | 13.8 |
| Sum Alkanes | 99.1 | 438.0 | 246.7 | 420.8 | 81.5 |
| Sum Aromatics | 32.1 | 284.8 | 105.3 | 112.4 | 41.9 |
| Sum NMHC | 146.0 | 808.9 | 398.5 | 636.4 | 141.0 |
| Percent Tailpipe Emissions | 34 | 61 | 40 | 99 | 42 |
| Airport Wind Direction(a) | 190° | 130° | 170° | 160° | 180° |
| Wind Speed, mph(a) | 16.1 | 8.1 | 6.9 | 5.8 | 17.3 |

(a) For the one hour preceding the sample.

relatively higher values of acetylene and thus greater percentages attributed to tailpipe emissions.

### 3.5.7 Distributions of Hydrocarbons From South to North at the Surface and Aloft

Distribution of selected hydrocarbons as measured at the surface for 5 days at sites south, north, and in Tulsa are compiled in Table 3.39. Wind direction on each of these days was from the south. Samples from the southern site, Liberty Mounds, and the city CBD site, the Post Office, were taken during the period 0600 to 0900 CDT. Data from the northern surface sites were taken during the afternoon hours 1400 to 1700 CDT.

During the 0600 to 0900 CDT time period, the aircraft performed a vertical spiral over the southern and city sites. Data for the corresponding aircraft samples at 760 m (2,500 ft) MSL altitude are given in Table 3.40. Comparison of the data in the two tables shows that at the upwind site, concentrations near the surface always exceeded those of the concurrent samples taken aloft. Samples taken at altitudes higher than 760 m showed further decreases in concentrations of most species. Complete data from these samples are listed in Volume II of this report.

A shallow inversion layer, which is almost always present near the surface prior to the period 0600 to 0900 CDT, traps hydrocarbon from the emissions surface during the night. Thus, in the morning greater concentrations might to be expected at the surface than aloft. The small concentrations measured above the inversion layer (e.g., at 760 m and higher) indicate that there were no significant amounts of hydrocarbons coming from the south into the Tulsa area on the upper winds.

Surface hydrocarbon concentrations at the city Post Office were much higher than those of the background site. The increased concentration at the surface in the city was not reflected in the sample taken at an altitude of 760 km (2,500 ft) MSL immediately north of the central business district. Only in one case, September 16, was the sum of NMHC over the city substantially higher than the surface background. A corresponding increase in acetylene concentration is noted in this sample, indicating urban vehicular origin.

## TABLE 3.39. HYDROCARBON DISTRIBUTIONS AT THE SURFACE SOUTH, IN, AND NORTH OF TULSA; CONCENTRATIONS IN ppbC

| Date | | 8/26 | | | 9/2 | | | 9/3 | | | 9/16 | | | 9/17 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample Number | 1043 | 3043 | 4002 | 1052 | 3052 | 6002 | 1054 | 3054 | 5003 | 1070 | 3071 | 5005 | 1072 | 3073 | 5006 |
| Location[a] | South | CBD | North | South | CBD | North | South | CBD | North | South | CBD | North | South | CBD | North |
| Ethylene | - | 48.2 | 6.5 | - | 62.2 | 15.4 | - | 37.4 | - | - | 59.0 | - | - | 33.6 | - |
| Propane | 27.0 | 40.5 | 11.2 | 104.4 | 50.7 | 10.2 | - | 20.4 | 26.1 | 67.5 | 54.0 | 16.2 | 22.8 | 21.3 | 10.5 |
| Acetylene | 1.6 | 29.2 | 4.5 | 1.0 | 30.0 | 1.2 | 2.0 | 12.0 | 5.2 | 3.6 | 45.4 | 1.8 | 1.0 | 7.6 | 1.8 |
| n-Butane | 16.8 | 53.2 | 20.0 | 36.0 | 60.4 | 10.8 | 8.0 | 40.0 | 21.2 | 23.2 | 112.0 | 5.3 | 8.4 | 21.2 | 7.6 |
| Propylene | 5.4 | 6.9 | 4.5 | 2.0 | 14.4 | 0.6 | 0.0 | 6.3 | 0.0 | 1.5 | 18.9 | 0.0 | 3.0 | 3.0 | 2.4 |
| Isopentane | 11.0 | 47.0 | 20.0 | 24.0 | 70.0 | 7.5 | 0.0 | 47.0 | 23.0 | 15.5 | 111.5 | 2.4 | 7.0 | 18.5 | 7.0 |
| m-Xylene | 0.0 | 3.7 | 1.0 | 0.1 | 9.6 | 0.1 | 0.1 | 5.6 | 0.2 | 0.1 | 9.6 | 1.5 | 1.0 | 1.3 | 0.2 |
| ΣAlkenes | 6.3 | 57.3 | 17.3 | 3.5 | 79.8 | 17.1 | 1.3 | 51.0 | 3.2 | 1.5 | 85.3 | 0.7 | 3.0 | 37.9 | 3.4 |
| ΣAlkanes | 106.3 | 312.2 | 119.2 | 280.1 | 419.6 | 48.3 | 25.3 | 230.4 | 118.8 | 159.7 | 638.9 | 37.3 | 63.6 | 125.7 | 43.9 |
| ΣAromatics | 11.2 | 166.2 | 49.4 | 18.3 | 110.7 | 82.4 | 15.0 | 73.5 | 22.6 | 5.8 | 100.9 | 37.2 | 57.0 | 53.4 | 64.2 |
| ΣNMHC | 125.4 | 564.9 | 190.4 | 302.9 | 640.1 | 149.0 | 43.6 | 366.9 | 149.8 | 170.6 | 870.5 | 77.0 | 124.6 | 224.6 | 113.3 |

[a] South: Morning samples at Liberty Mounds site. CBD: Morning samples at Post Office site. North, afternoon samples: 8/26, Sperry; 9/2, Ochelata; 9/3, Vera; 9/16, Vera; 9/17, Vera.

TABLE 3.40. HYDROCARBON DISTRIBUTIONS AT 2,500 FT MSL SOUTH, OVER, AND NORTH OF TULSA

| Date |  | 8/26 |  |  | 9/2 |  |  | 9/3 |  |  | 9/16 |  |  | 9/17 |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample Number | 9002 | 9005 | 9008 | 9011 | 9014 | 9018 | 9021 | 9024 | 9028 | 9040 | 9043 | 9046 | 9049 | 9052 | 9056 |
| Location(a) | South | CBD | North | South | CBD | North | South | CBD | North | South | CBD | North | South | CBD | North |
| Ehtylene | 0.0 | 3.6 | 26.6 | 6.6 | 1.8 | 10.4 | 1.2 | 2.0 | 3.4 | 3.2 | 7.2 | 9.0 | 3.6 | 1.6 | 2.8 |
| Propane | 4.2 | 4.2 | 12.3 | 2.4 | 2.7 | 10.8 | 1.2 | 1.5 | 9.3 | 13.5 | 15.0 | 9.0 | 8.4 | 2.1 | 7.5 |
| Acetylene | 0.0 | 1.0 | 5.0 | 0.0 | 1.0 | 2.0 | 0.0 | 0.0 | 2.2 | 0.0 | 3.0 | 1.2 | 0.0 | 0.0 | 0.0 |
| n-Butane | 1.2 | 0.8 | 20.4 | 3.2 | 0.0 | 14.4 | 0.0 | 0.0 | 7.6 | 8.0 | 13.2 | 5.2 | 5.2 | 0.0 | 4.8 |
| Propylene | 0.0 | 0.6 | 3.0 | 6.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.1 | 7.2 | 1.8 | 0.0 | 0.0 |
| Isopentane | 0.0 | 0.0 | 217.5 | 0.0 | 0.0 | 8.5 | 0.0 | 0.0 | 5.0 | 0.0 | 100.0 | 3.0 | 0.0 | 0.0 | 1.5 |
| m-Xylene | 0.1 | 0.0 | 12.6 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.3 | 0.1 | 1.3 | 0.1 | 0.1 |
| ΣAlkenes | 0.2 | 4.2 | 30.8 | 13.6 | 1.8 | 12.9 | 1.7 | 3.4 | 5.4 | 5.3 | 9.3 | 16.9 | 3.6 | 1.6 | 2.8 |
| ΣAlkanes | - | - | 2621.5 | 9.8 | 7.7 | 54.5 | 2.8 | 24.2 | 34.5 | 53.3 | 251.1 | 316.1 | 27.4 | 5.1 | 28.2 |
| ΣAromatics | 26.6 | 31.4 | 525.4 | 146.5 | 20.3 | 61.7 | 35.2 | 20.3 | 6.6 | 11.5 | 113.5 | 29.4 | 24.1 | 6.7 | 19.9 |
| ΣNMHC | - | - | 3182.7 | 169.9 | 30.8 | 131.1 | 39.7 | 47.9 | 48.7 | 72.5 | 376.9 | 363.6 | 56.3 | 13.4 | 50.9 |

(a) South: Morning spiral over Liberty Mounds site. CBD: Morning spiral immediately north of the downtown central business district. North, afternoon spirals: 8/26, Sperry; 9/2, Ramona; 9/3, 8 km east of Vera; 9/16, Talala; 9/17, Nowata.

(b) These concentrations are unusually high. The possibility of contamination of the sample cannot be ruled out.

Integrated samples were collected at all northern ground sites during the hours 1400 to 1700 CDT. By this time of day the atmosphere was well mixed and emissions from Tulsa, which drift northward on the winds, would be expected to be appreciably diluted. The data seem to indicate, for these few cases, that the strength of urban hydrocarbon plumes varied considerably with altitude and distance from the source. For example, on August 26, the aircraft sampled an airspace above Sperry that was rich in hydrocarbons, yet the corresponding surface sample concentration was over an order of magnitude lower. A recognized confounding feature in comparing these two samples was the length of sampling time. The aircraft, with its short sampling period, may have fortuitously sampled an air parcel having extremely high hydrocarbons.

Surface and airborne samples taken farther north in the vicinity of the maximum ozone plume (such as those of September 2 and 3) show NMHC concentrations substantially lower than those present in morning samples in the city (but still contain acetylene concentrations greater than those in samples taken upwind in the morning). There are several reasons for this. First, the increased mixing of the atmosphere in the afternoon allowed greater dispersion and dilution; second, reactive hydrocarbons were removed by photochemical processes; and third, local (mesoscale) trajectories indicate that the air parcel sampled during the period 1400 to 1700 CDT downwind of the city was usually not the same parcel that passed through the city at the time of the morning sample. The air parcel passed through later in the morning, after peak traffic had subsided.

### 3.5.8 Correlation between NMHC by Sum of Species and by Continual Chromatography

At both city sites, the Post Office and the Health Department, concurrent samples for 0600 to 0900 CDT nonmethane hydrocarbons were taken in two ways: by summing the concentrations of individual hydrocarbons in integrated samples and by averaging three hourly values of NMHC obtained by the Beckman 6800 Environmental Chromatographs.

Regression analysis was performed to compare the results of the two methods in determining NMHC in ppmC. At the Post Office site, for 37 cases, the regression equation is:

(NMHC, Beckman) = 0.8034 (NMHC, sum of species) + 0.1417.

The correlation coefficient, R, is 0.9415; $R^2$ is 0.8867.

At the Health Department site, for 45 cases, the regression equation is:

(NMHC, Beckman) = 0.4590 (NMHC, sum of species) + 0.0903.

The correlation coefficient, R, is 0.453; $R^2$ is 0.2050.

As the equations indicate, the correlation between NMHC (Beckman) and NMHC (sum of species) is quite good for samples at the Post Office site and is poor for samples at the Health Department site. Examination of individual days of data from the Health Department site shows that the concentration of NMHC, as determined by the Beckman 6800, is sometimes less, sometimes greater, and sometimes nearly the same as the concentration determined by summing species. During the field program, there were frequently problems with zero and span drift with the analyzer at this site, as shown by frequent zero and span gas checks.

Comparison of daily concentration values for NMHC from the Post Office site shows generally good agreement between the two methods and few instances of extreme disagreement. NMHC by sum of species averages about 6 percent higher than NMHC as determined by the automated chromatograph. The agreement is unexpectedly good, however, as earlier field and laboratory experiments(13) have shown that NMHC obtained by summing individual hydrocarbon concentrations might have been expected to be even higher than those found in this study. One reason for this finding may be that a maximum of only 47 individual hydrocarbons were quantified, and this number obviously does not account for all hydrocarbons present in ambient air.

In summary, it appears that NMHC concentrations recorded by the Beckman 6800 at the Post Office site correlate well with NMHC by sum of species and could be used as surrogate values for 0600 to 0900 CDT or other time periods. On the other hand, values for Beckman NMHC concentrations at the Health Department seem to be questionable and data should be selected for study only for those days that had 0600 to 0900 CDT concentrations in reasonable agreement with NMHC by sum of species.

### 3.5.9 Comparison of Hydrocarbons from GC/FID and GC/Mass Spectrometry Studies

Five Tenax samples were collected and qualitatively analyzed for volatile organics by gas chromatography/mass spectrometry. Profiles of total ion current versus order of elution from the column (e.g., mass spectrum number) are given in Volume II of this report. Tables listing the compounds identified are also given in Volume II.

As many as 200 different compounds were identified in a 0600 to 0900 CDT Tenax sample taken at the downtown Post Office site on September 21, 1977. The composition of this sample (or the other four samples) consisted of an assortment of alkanes, alkenes, alkyl aromatics, oxygenated compounds, and halogenated compounds. About 83 percent of the compounds are hydrocarbons.

On September 21, samples were also collected at the background site, Liberty Mounds, during the period 0600 to 0900 CDT and at the Vera site (about 35 km north of the city) during the 1400 to 1700 CDT period. Table 3.41 presents a quantitative comparison (in arbitrary units) of volatile organics at these three stations. A significant increase in the relative quantity of alkanes, alkenes, alkyl aromatics, benzene, toluene, and ketones occurred as the ambient air was transported from Liberty Mounds through downtown Tulsa. Components of the sample taken at Vera were not as high in concentration as in the sample taken in the city. This is a reflection of the effects of compound removal by chemical reaction and by dilution due to increased atmosphere mixing in the afternoon.

When the 47 compounds identified and quantified by gc/fid in the sum of species task are compared to those identified by gc/ms, it is found that gc/ms identifies 28 by name and 10 by molecular formula. Six of the low molecular weight compounds "break through" the Tenax cartridge and are not retained in quantities sufficient for identification. These compounds are ethane, ethylene, acetylene, isobutane, propylene, and isoprene. Three higher molecular weight compounds were not identified by name or formula by gc/ms. These are 1-hexane, m-ethyltoluene, and o-ethyltoluene.

Hydrocarbons identified by name in the gc/ms study, which were not searched for in the gc/fid sum of species study, include methylcyclopentane, cyclohexane, 2,2-dimethylpentane, ethylcyclohexane, ethylbenzene, styrene,

TABLE 3.41. QUANTITATIVE COMPARISON OF VOLATILE ORGANICS BY TENAX GC/MS IN AMBIENT AIR FROM LIBERTY MOUNDS, TULSA, AND VERA, OKLAHOMA

| Chemical Class | Site | | |
|---|---|---|---|
| | Liberty Mounds | Post Office, Tulsa | Vera |
| Alkanes ($\geq C_6$) | 4.61 ± 0.28 | 15.92 ± 1.15 (3.4)[a] | 6.87 ± 0.74 (1.5) |
| Alkenes ($\geq C_6$) | 4.56 ± 0.06 | 11.67 ± 1.20 (2.5) | 5.79 ± 0.59 (1.3) |
| Alkyl aromatics ($\geq C_8$) | 3.36 ± 0.62 | 10.82 ± 0.99 (3.2) | 3.64 ± 1.18 (1.1) |
| Benzene | 0.25 ± 1.13 | 0.43 ± 0.01 (1.7) | 0.10 ± 0.01 (0.4) |
| Toluene | 0.43 ± 0.10 | 3.74 ± 0.46 (8.7) | 0.29 ± 0.03 (0.7) |
| Aldehydes ($\geqq C_6$) | 3.60 ± 0.46 | 1.36 ± 0.07 (0.38) | 0.72 ± 0.28 (0.2) |
| Ketones ($\geqq C_3$) | 0.51 ± 0.06 | 1.74 ± 0.20 (3.4) | 0.13 ± 0.5 (0.2) |
| Phenols ($\geq C_7$) | 2.34 ± 0.26 | 1.38 ± 0.03 (0.6) | 1.82 ± 0.46 (0.7) |
| Misc. oxygenates ($\geq C_4$) | 1.91 ± 0.39 | 0.89 ± 0.51 (0.5) | 0.87 ± 0.30 (0.5) |
| Light hydrocarbons ($C_3$-$C_5$) | 0.81 ± 0.07 | 0.39 ± 0.06 (0.5) | 0.12 ± 0.07 (0.1) |

[a] Values in arbitrary units/$m^3$ of air, numbers in parenthesis relative to Liberty Mounds.

isopropylbenzene, several naphthalenes, n-tridecane, n-pentadecane, and n-hexadecane.

## 3.6 ANALYSIS AND INTERPRETATION OF AIRCRAFT DATA

### 3.6.1 Analysis Approach

An instrumented aircraft collected data on 2 days in August and on 7 days in September, to determine the horizontal distribution at 2,500 ft and vertical distribution of meteorological and pollutant parameters in the study area. In this section, the general features of the aircraft data are examined. The aircraft flights were divided into morning flights upwind of Tulsa, and afternoon flights downwind of Tulsa. Horizontal traverses were flown on all of the flights, and vertical spirals to 10,000 ft MSL were flown on most of the individual flights.

A general description of the background ozone concentrations on both the horizontal and vertical portions of each flight is presented first. The horizontal and vertical segments of the flights are considered separately in more detail. Finally, comparisons are made between measurements made aboard the aircraft and the surface measurements made at stations below the flight paths and locations of the vertical spirals.

The aircraft data were plotted and appear in Volume II of this report. Individual data points at 15-second intervals also appear in Volume II.

### 3.6.2 Background Ozone Concentrations on the Aircraft Flights

A summary of the mean background ozone concentrations and standard deviations for each of the aircraft flights appears in Table 3.42. The term background is not meant to imply that the ozone concentrations listed in the table were solely the result of natural sources. These concentrations were considered to represent the background burden, however, because they were quite stable over the individual flights, as indicated by the small standard deviations, and the source areas of these ozone concentrations could not be identified. These background concentrations were determined by averaging the individual 15-second data points over the sections of each aircraft flight that were not obviously in the Tulsa urban plume. The background ozone concentrations on the vertical spirals were obtained similarly and

TABLE 3.42. BACKGROUND OZONE CONCENTRATIONS OF AIRCRAFT FLIGHTS

a.m. Flights

| Flight No. | Date | Mixing Height, ft. MSL | Avg. Background $O_3$, ppm | | | |
|---|---|---|---|---|---|---|
| | | | Horizontal | | Spiral | |
| | | | Mean | S.D. | Mean | S.D. |
| T03 | 25 Aug | - | .071 | .004 | - | - |
| T05 | 26 Aug | <1100 | .060 | .002 | .064 | .005 |
| T09 | 2 Sept | <1100 | .064 | .007 | .052 | .005 |
| T11 | 3 Sept | <1100 | .078 | .005 | .071 | .006 |
| T14 | 8 Sept | - | .076 | .006 | - | - |
| T16 | 11 Sept | <1100 | .072 | .005 | .066 | .003 |
| T17 | 16 Sept | <1100 | .068 | .003 | .061 | .003 |
| T19 | 17 Sept | <1100 | .049 | .002 | .051 | .004 |
| p.m. Flights | | | | | | |
| T04 | 25 Aug | - | .078 | .004 | - | - |
| T06 | 26 Aug | 4000 | .073 | .004 | .072 | .003 |
| T10 | 2 Sept | 5500 | .078 | .006 | .061 | .007 |
| T12 | 3 Sept | - | .091 | .007 | .095 | .007 |
| T15 | 9 Sept | 6500 | .074 | .004 | .062 | .003 |
| T18 | 16 Sept | 5200 | .076 | .004 | .054 | .005 |
| T20 | 17 Sept | 6300 | .064 | .003 | .051 | .005 |

data points included in layers with elevated ozone concentrations were not included in the average. The consistency observed in the background ozone concentrations within individual flights results from mixing of ozone and ozone precursors before they arrive in the Tulsa area.

During most of the afternoon flights, an urban ozone plume with a width only slightly greater than the width of the city of Tulsa, and centered nearly in line with the mean surface winds, was observed downwind of Tulsa. When the ozone concentration increased steadily to values more than 0.010 ppm above the background, it was assumed that the aircraft was sampling within the urban plume. The ozone concentrations beyond the point of the steady rise within the plume were not included in the average for the background concentrations. On most of the morning flights upwind of Tulsa a relatively homogeneous horizontal distribution of ozone was observed, and each data point on the horizontal traverses was included in the calculation of the average background ozone concentration. The consistency observed in the background ozone concentration within individual flights results from mixing of ozone and ozone precursors before they arrive in the Tulsa area.

On the vertical spirals of many of the morning flights a shallow layer with increased ozone concentrations was observed. These layers were centered typically between 2,000 ft and 4,000 ft MSL. The available data provide no evidence as to the cause of this observation. During the afternoon flights, much deeper layers of elevated ozone were often observed from the lowest altitude of the spiral up to altitudes above 6,000 ft. These layers were almost certainly produced by vertical mixing of the Tulsa plume. Unfortunately, upwind spirals were not flown in the afternoon, and no spirals were flown downwind of Tulsa during the morning flights. The ozone concentrations within the layers of elevated ozone on the morning flights were not included in the average background concentration. In all cases, only the concentrations measured above the maximum vertical extent of the urban plume were included in the calculation of the background ozone concentration on the spirals during the afternoon flights.

The minimum horizontal flight background ozone concentration listed in Table 3.42 is 0.049 ppm. The average background for eight morning flights is 0.067 ppm ozone. It is suspected that the background ozone concentrations measured on the morning flights had an impact on the ozone concentrations measured at the surface once the nocturnal inversion was destroyed and mixing near the surface had been established. Without the availability of an objective and reliable model of near-surface vertical mixing and photochemistry, it is not possible to quantify that impact. These data do suggest, however, that the atmosphere is capable of storing relatively high concentrations of ozone, and that the background ozone burden above nocturnal inversions may need to be considered in developing efficient control strategies.

In almost every case the background ozone concentrations observed on the afternoon flights exceeded those of the morning flights. The average increase in the background ozone concentration on the 6 days that had both morning and afternoon flights was 0.012 ppm. Assuming that the immediate impact of the Tulsa metropolitan area was confined to the region that could be identified as the Tulsa plume, these data imply that the chemical composition of the background air was photochemically active, even though very little $NO_x$ or NMHC was measured aboard the aircraft. Although the ozone synthesis observed in the background air near Tulsa was minor, neglecting the influence may lead to inaccurate predictions of maximum surface ozone concentrations.

### 3.6.3 Analysis of the Horizontal Traverses

In addition to ozone, temperature, dew point, $b_{scat}$, and in some cases condensation nuclei were measured on the horizontal traverses. NO and $NO_x$ were also measured, but the concentrations were rarely more than the minimum detectable limit of the instrument (0.005 ppm) and therefore have not been included in the following analyses. The plots of these data appear in Volume II. On each of the morning flights, except flight T19 on September 17, 1977, each of the parameters was nearly constant on each horizontal traverse south of Tulsa.

On flight T19 the ozone concentrations changed rapidly, on each horizontal traverse, in a way that suggests the presence of an ozone plume. There were also some small variations in the ozone concentrations on the horizontal traverses over and just north of Tulsa on most of the flights. The variations in the ozone concentration near Tulsa in the horizontal legs of morning flights are assumed to be caused by remnants of urban photochemical activity of Tulsa of the preceding day. However, the rapidly increasing ozone concentrations observed on flight T19 were seen as far south as Liberty Mounds, and the cause of this phenomenon is unknown.

There was a maximum in wind speed of approximately 60 mph between 2,000 and 3,000 ft from 200° determined by a pibal release at 0530 on September 17, 1977, at the Tulsa International Airport. The vertical profile of temperature measured during the spiral at Liberty Mounds shows that the same layer was stable, which would inhibit mixing. The cause of the elevated ozone and its relationship to the other factors mentioned above is not clear. There is a possibility, however, that the high wind speeds could have transported that ozone from some other urban area and the stability within that same layer, present throughout the night, may have inhibited mixing. The synoptic trajectories for September 17, 1977, show that the air arriving in Tulsa at 0600 CST had passed near the Dallas-Ft. Worth area 12 hours earlier. A layer of high ozone concentration between 2,000 ft and 3,000 ft that had rapidly changing ozone concentrations with altitude was measured on the vertical spiral at Liberty Mounds. Another possible explanation of the plume-like appearance of ozone on the horizontal traverses is that the boundary of that layer may have changed altitude along the horizontal traverse in such a way that the aircraft flew into the region of high ozone concentration. On all of the morning flights the $b_{scat}$ and condensation nuclei data were nearly constant across the horizontal traverses. There were some small positive excursions in the condensation nuclei data that probably were caused by local sources.

The ozone data from the afternoon horizontal traverses often showed an urban ozone plume extending to the north of Tulsa. Regions of the downwind horizontal traverses were considered to be within the Tulsa urban plume if the ozone concentrations increased steadily and reached concentrations at least 0.010 ppm higher than the average background. A list of the afternoon flights with pertinent meteorological information, the background and peak ozone concentrations, and the plume half-width is given in Table 3.43. The ozone plumes measured on flights T10, T12, and T15 were very well defined and have a shape and location that implicates Tulsa as the source. The center lines of these plumes were approximately in line with the mean surface winds leaving Tulsa, except for the apparent plume measured on September 9 on flight T-15. In each case the width of the regions of elevated ozone were on the order of the width of Tulsa. Unfortunately, no upper air wind directions were available from Tulsa for flight T15 on September 9. The surface winds were from the northwest, and the ground stations north of Tulsa measured relatively low ozone concentrations all day. The rawinsonde observations at 0600 and 1800 CST from September 9 at Oklahoma City suggest that upper air winds were also from the northwest. The source of that ozone plume, therefore, is unknown. The aircraft's vertical temperature profile indicates that a layer of stable air near the surface extended to a height of approximately 3,000 ft. The stability may have decreased turbulent exchange of mass between 2,500 ft and the surface.

On 3 of the 4 days with distinct ozone plumes, the maximum ozone concentration was measured on leg 5, approximately 48 km (30 mi) downwind of

## TABLE 3.43. SUMMARY OF AFTERNOON AIRCRAFT FLIGHT DATA

| Flight Number | Wind[(a)] Dir. | Wind[(a)] Speed, mph | General sky condition | % Possible sunshine | Horizontal leg number | $O_3$ Concentration, ppm Background Mean | $O_3$ Concentration, ppm Background S.D. | $O_3$ Concentration, ppm Peak[b] | Plume half width, mi. |
|---|---|---|---|---|---|---|---|---|---|
| T04 (8-25) | 175° | 15.5 | Broken low & high altitude | 85 | 1 | .079 | .004 | 0.098 | - |
| | | | | | 3 | .077 | .004 | - | - |
| T06 (8-26) | 198° | 17.2 | Scattered low altitude | 89 | 1 | .073 | .003 | 0.089 | 7.5 |
| | | | | | 3 | .072 | .003 | 0.089 | 9.0 |
| | | | | | 5 | .073 | .003 | 0.090 | 7.5 |
| | | | | | 7 | .075 | .005 | 0.084 | - |
| T10 (9-2) | 186° | 4.7 | Scattered low and high altitude | 89 | 1 | .075 | .007 | 0.141 | 12.0 |
| | | | | | 3 | .079 | .006 | 0.144 | 15.0 |
| | | | | | 5 | .081 | .006 | 0.156 | 10.5 |
| | | | | | 7 | .079 | .004 | 0.154 | 10.5 |
| T12 (9-3) | 192° | 8.2 | Scattered low altitude | 83 | 1 | .096 | .005 | 0.190 | 10.5 |
| | | | | | 3 | .089 | .004 | 0.207 | 9.0 |
| | | | | | 5 | .093 | .011 | 0.164 | 12.0 |
| | | | | | 7 | .083 | .003 | 0.136 | 9.0 |
| T15 (9-9) | 307° | 9.8 | Scattered low altitude -clear | 84 | 1 | .072 | .005 | 0.111 | 7.5 |
| | | | | | 3 | .075 | .003 | 0.116 | 12.0 |
| | | | | | 5 | .075 | .002 | 0.122 | 10.0 |
| | | | | | 7 | .076 | .002 | 0.119 | 12.0 |
| T18 (9-16) | 160° | 8.8 | Broken low altitude | 44 | 1 | .076 | .004 | - | - |
| | | | | | 3 | .075 | .003 | - | - |
| | | | | | 5 | .076 | .004 | - | - |
| | | | | | 7 | .078 | .005 | - | - |
| T20 (9-17) | 192° | 11.5 | Broken high altitude | 92 | 1 | .063 | .003 | - | - |
| | | | | | 3 | .064 | .002 | - | - |
| | | | | | 5 | .065 | .003 | - | - |
| | | | | | 7 | .066 | .004 | - | - |

(a) Average from 1000 through 1500 CST at the Health Department site.
(b)15 second measurement interval.

Tulsa. On the remaining day, September 3, the maximum ozone concentration was measured on leg 3, approximately 32 km (20 mi) downwind of Tulsa. There is no evidence to indicate that higher ozone concentrations were not present farther downwind at later times. It is interesting that the urban ozone plume did not experience a significant amount of spread in traveling the 64 km (40 mi) to the location of the final horizontal traverse. The plume half-width was used as the measurement of the plume spread because in some cases only half of the plume was observed within the limits of the flight tracks. The plume half-width was determined by taking the distance from the point of maximum ozone concentration to the point where the ozone concentration had fallen to a value 0.005 ppm above the background ozone concentration. The average plume spread on all horizontal traverses was approximately 34 km (21 mi). The city of Tulsa is approximately 26 km (16 mi) wide in the east to west direction. Therefore, the ozone plume from Tulsa was only slightly wider than Tulsa and did not widen appreciably in traveling the 64 km downwind.

For the most part, the $b_{scat}$ data were highly consistent across the horizontal traverses of each flight. On each of the flights that had well-defined ozone plumes (T10, T12, and T15), increased concentrations of condensation nuclei were measured in approximately the same locations as the increased ozone concentrations. It would appear that the condensation nuclei measured in these plumes represented small particle formation from photochemical processes.

The condensation nuclei measured on flight T18 on September 16, 1977, showed the most variation of any of the flights, despite the fact that there was no evidence of an ozone plume. On the vertical spiral from that flight, very low concentrations of CN were measured over the entire spiral and therefore the origin of the condensation nuclei measured on the horizontal traverses is unknown.

The net impact of Tulsa on ozone formation at 2,500 ft MSL can be estimated. The difference between the maximum ozone concentration measured in each plume, and the background ozone measured on the same horizontal leg was assumed to represent the net impact of Tulsa on ozone formation. Concentrations obtained in this way for flights T04, T06, T10, T12, and T15 were

0.023, 0.020, 0.076, 0.117, and 0.047 ppm, respectively. With the exception of flight T12, the net ozone at 2,500 ft MSL was similar to that determined at the surface for several of the case study days, to be discussed later.

### 3.6.4 Analysis of Vertical Spiral Profiles

The normal flight plan for morning flights called for two vertical spirals. Each morning flight, with the exceptions of flights T03 on August 25 and T14 on September 8, 1977, began with a vertical spiral over Liberty Mounds, from an altitude between 1,100 and 1,500 ft up to an altitude of 10,000 ft MSL. A second vertical spiral was flown over the central business district of Tulsa, at the end of each of the flights, except flight T17 on September 16, 1977. The second spiral was flown from an altitude between 2,500 ft and 3,000 ft MSL to an altitude of 10,000 ft MSL. At least one layer with high ozone concentrations relative to the spiral background could be identified on each spiral at Liberty Mounds. With the exception of a high-altitude layer at 8,250 ft MSL on flight T05, those layers of high ozone were similar in appearance and occurred at similar altitudes. In addition, the same type of layers with high ozone concentrations were often measured in the central business district spirals. A list of the morning flights with the altitudes of the maximum ozone and the difference between the maximum ozone concentration in the layers and the average background ozone concentration on the spirals appears in Table 3.44. There is at least one layer with ozone concentrations that are at least 0.010 ppm greater than the average background on each spiral at Liberty Mounds and on all but one of the spirals over the central business district.

Data from one vertical spiral are available from each afternoon flight, except flight T04 of August 25, 1977. The ozone data from the spirals of the afternoon flights are much different in appearance than those of the morning flights. Deep layers with elevated ozone concentrations were observed on the spirals of all the afternoon flights except flight T06 on August 26, 1977. In all cases the regions of elevated ozone on the afternoon spirals began at the lowest point on the spiral and extended up to an altitude of at least 4,000 ft MSL. Table 3.45 lists the afternoon flights that had layers with increased ozone on the lower half of the spirals, the altitude to which

TABLE 3.44. ALTITUDE AND CONCENTRATION OF MAXIMUM OZONE DURING MORNING AIRCRAFT SPIRALS

| Flight number | Location | Altitude of ozone maxima, ft MSL | Max. ozone concentration, ppm | Max. ozone less avg. background |
|---|---|---|---|---|
| T05 | Mounds | 8250 | 0.087 | 0.022 |
| | CBD | 8250 | 0.084 | 0.019 |
| T09 | Mounds | 2950 | 0.085 | 0.035 |
| | CBD | 2800 | 0.070 | 0.020 |
| T11 | Mounds | 2550 | 0.084 | 0.014 |
| | CBD | 3150 | 0.081 | 0.011 |
| | CBD | 4150 | 0.100 | 0.030 |
| | CBD | 9550 | 0.086 | 0.016 |
| T16 | Mounds | 3600 | 0.081 | 0.016 |
| | Mounds | 5150 | 0.087 | 0.022 |
| | CBD | 3900 | 0.089 | 0.024 |
| | CBD | 5350 | 0.084 | 0.019 |
| T17 | Mounds | 3350 | 0.106 | 0.046 |
| T19 | Mounds | 2400 | 0.075 | 0.025 |

the layers extended, the maximum ozone concentration measured, the altitude of the maximum ozone concentration, and the difference between the maximum and average background ozone concentrations. Because the afternoon spirals took place downwind of Tulsa, it is assumed that these ozone layers represented ozone generated by surface emissions and mixed by thermal processes to the altitudes given in Table 3.45. These ozone layers were often associated with horizontal ozone plumes, and therefore the altitude to which the ozone was mixed is assumed to represent the vertical extent of the urban ozone plume. The concentrations of the other parameters measured do not coincide with the deep layer of elevated ozone observed on the afternoon spirals.

### 3.6.5 Comparison of Aircraft and Ground-Based Ozone Measurements

The aircraft measurement program provided data for comparing ground-level ozone measurements to much shorter time-averaged ozone measurements made aboard the aircraft in three distinct altitude regimes. Ozone concentrations measured aboard the aircraft during low-approach flight segments at

TABLE 3.45. ALTITUDE AND CONCENTRATION OF MAXIMUM OZONE DURING AFTERNOON AIRCRAFT SPIRALS

| Flight number | Location | Maximum altitude, ft, MSL, of ozone layer* | Maximum ozone, ppm | Altitude of max. ozone | Max. ozone less avg. background |
|---|---|---|---|---|---|
| T10 | Ramona | 6000 | 0.150 | 2050 | 0.090 |
| T12 | Ramona | 6350 | 0.161 | 2150 | 0.066 |
| T15 | Ramona | 7050 | 0.120 | 4250 | 0.055 |
| T18 | Talala | 6800 | 0.086 | 3550 | 0.031 |
| T20 | Nowata | 4350 | 0.073 | 2500 | 0.023 |

*Altitude above which the ozone concentration is less than 10 ppb higher than the average background ozone concentration on the spiral.

50 ft AGL, at the bottom of vertical spirals, and on segments of horizontal traverses above surface stations were compared to hourly average surface ozone concentrations. Each of the three comparisons was influenced by the different time averages of the samples, and in some cases by considerable horizontal distances between the locations of the two samples. The ozone data collected on low-altitude approaches at approximately 50 ft AGL, over runways at Okmulgee Airport, Tulsa Downtown Airport, and Tulsa International Airport, were compared to hourly average surface data from the Liberty Mounds station, located 22 km (13.9 mi) north of Okmulgee Airport; the Post Office station, 7.7 km (4.8 mi) south of Tulsa Downtown Airport; and the Health Department station, 7.4 km (4.6 mi) southwest of Tulsa International Airport.

The comparisons between the two sets of data were made by calculating linear regression parameters and correlation coefficients (r-values). The correlation for comparison of afternoon low-approach flight data to the surface ozone data, with an r-value of 0.885, was much better than the correlation for low approaches from the morning flights of 0.621. All of the afternoon low approaches were done at Okmulgee Airport and the higher correlation for afternoon flights was observed in spite of the large horizontal distance between the aircraft and surface measurements. The linear regression equation obtained for the comparison of afternoon low-approach data with the surface station data was:

$$[O_3] \text{ 50 ft AGL} = -0.029 + 1.777 [O_3] \text{ Liberty Mounds.}$$

The regression equation for the comparison of morning low-approach data with the surface station data, which included low approaches at all three of the locations, was:

$$[O_3] \text{ 50 ft AGL} = 0.021 + 0.722 [O_3] \text{ Surface.}$$

When all of the data collected on low approaches at Okmulgee Airport, on both morning and afternoon flights, were compared to the corresponding Liberty Mounds surface data, a correlation of 0.941 was obtained. Although the number of data pairs used to calculate these correlations is not sufficient to establish any meaningful conclusions, it is apparent that the ozone concentration in the upwind rural area around Okmulgee and Liberty Mounds was, on the average, more homogeneous than that in the city of Tulsa. This was true even though the horizontal distance between the locations of the two measurements was much greater for the rural case. This result was expected since local sources and morning traffic at the urban locations influence both the production and destruction of ozone.

During the morning flights, vertical spirals were usually flown over the Liberty Mounds station and over the central business district in close proximity to the Post Office station. The temperature profiles from the morning spirals indicate that the surface inversion probably kept the effective mixing height below 1,100 ft MSL in all cases. The presence of a nocturnal inversion serves to isolate the near-surface atmosphere from the atmosphere above the inversion. Therefore, a strong relationship is not expected between the spiral base ozone concentration and the surface ozone concentration on the morning flights. The correlation coefficient calculated for these data was -0.563, which indeed implies that no relationship existed between the measurements.

There were two specific spirals for which the spiral base ozone concentrations exceeded the surface concentration by less than 0.010 ppm. On both of these days the wind speeds during the time of the spiral measured on a 40-ft tower at the Health Department station were in excess of 13 mph. On the remaining flights, which had differences in ozone concentrations between the spiral base and surface station in excess of 0.030 ppm, the wind speeds measured at the Health Department were 6 mph or less. The Health Department wind speeds were used because it was felt that the winds measured on the tower were less influenced by surface effects than the winds measured on a 4-m tripod located at Liberty Mounds. Once again, the scarcity of data does not allow significant conclusions to be drawn; however, the data do suggest that high wind speeds may generate enough turbulence to keep the surface layer mixed in rural areas in the morning.

Four morning spirals were flown near the downtown Post Office station and even with wind speeds in excess of 12 mph the closest agreement observed between the spiral base ozone concentration and the ground station ozone concentration was 0.040 ppm. Therefore, the capacity for ozone scavenging near the surface in urban areas is probably sufficient to destroy the ozone near the surface even if the wind speeds are high enough to keep turbulent mixing active.

During the afternoon flights, a spiral was flown at the estimated location of maximum ozone. There were six afternoon spirals in all, with one flown near the Sperry ground station, two near the Vera ground station, and three near the Ochelata ground station.

A linear regression equation for all the afternoon spiral base ground station comparisons was found to be:

$$\text{Spiral base } [O_3] = -0.020 + 1.398\ [O_3] \text{ ground station, r-value} = 0.952.$$

Two of these data pairs had observed differences of only 0.002 ppm in ozone concentration between the spiral base and ground station. Wind speeds at the Health Department for these two cases were greater than 14 mph. This would imply that when sufficiently high wind speeds are present in the Tulsa area the air is well mixed up to at least 2,000 ft MSL. Wind speeds associated with the remaining four spirals were all 10 mph or less. Once again the limited amount of data is insufficient to make any definite conclusions. These data may suggest that with wind speeds less than 10 mph, the vertical mixing processes are not efficient enough to keep the lowest 2,000 ft MSL mixed homogeneously even in the absence of a nocturnal inversion.

Comparison of the ozone concentrations as averaged from three 15-second readings on the horizontal traverses of the morning flights at approximately

2,500 ft MSL to the nearest surface station measurement led to a correlation of -0.032. This result certainly implies that the influence of a nocturnal inversion does not allow mixing to altitudes as great as 2,500 ft.

A regression equation calculated for the horizontal traverse aircraft ozone concentration and the hourly average ground station ozone concentration for afternoon flights yielded the following relationship:

Aircraft $[O_3] = 0.033 + 0.731\ [O_3]$ ground station, r-value = 0.736.

It is difficult to interpret this result because the afternoon flights were flown at times when surface ozone concentrations were still changing due to photochemical synthesis. The differences in averaging times of the two measurements, as well as possible differences in transport rates at the surface and at 2,500 ft, may have influences that are impossible to describe completely.

# 4.0 ANALYSIS OF CASE STUDY DAYS

## 4.1 INTRODUCTION

Four groups of days were chosen for detailed analysis as case studies. The days chosen for these case studies include the periods July 21-25, July 28-30, August 2-5, and September 2 and 3. Within the first three of these groups of days the maximum ozone concentrations of the summer study at each station in the network were observed. The fourth case study period, September 2 and 3, was chosen for analysis because aircraft measurements were made on both days and a downwind ozone plume was observed at the surface and at 2,500 ft MSL.

In performing the case study analyses, a series of steps was followed. First, the meteorological conditions of each period were described in terms of influences observed in Tulsa. Air parcel trajectories describing air movement on both the synoptic scale and local scales were analyzed to help identify transport processes active during each day.

Next, the distribution of selected hydrocarbons and $NO_x$ at the upwind (Liberty Mounds) and city sites (Post Office and Health Department) during the 0600 to 0900 CDT sampling period is discussed. A list of the monthly and overall average concentrations and standard deviations of selected hydrocarbons and oxides of nitrogen is presented in Table 4.1 along with selected ratios. The concentrations of the same parameters and values of the same ratios for each case study day are included in the individual case study analyses. The distribution of maximum ozone concentrations and the length of time each station's ozone concentrations were in excess of 0.08 ppm are then presented.

Finally, a day-by-day discussion of each case study is given. Wherever appropriate, explanations of the observed concentration distributions and diurnal behavior of measured pollutants are discussed. Such explanations include, in most cases, the relationship between the daily active meteorological influences and the resultant chemical behavior within the network. Figures summarizing both the meteorological and chemical data utilized in the case study analyses appear in each individual case study discussion.

## TABLE 4.1. MONTHLY AVERAGES AND STANDARD DEVIATIONS OF SELECTED PARAMETERS

| | $\Sigma$NMHC, ppm | | | NMHC, Beckman, ppm | | | $\Sigma$Alkenes, ppm | | | Acetylene, ppm | | | n-Butane, ppm | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | Mean | S.D. | N | Mean | S.D. | N | Mean | S.D. | N | Mean | S.D. | N | Mean | S.D. |
| Post Office | | | | | | | | | | | | | | | |
| July | 15 | .430 | .153 | 17 | .471 | .184 | 15 | .050 | .016 | 18 | .010 | .005 | 18 | .060 | .046 |
| August | 29 | .682 | .620 | 24 | .703 | .570 | 29 | .068 | .029 | 31 | .022 | .013 | 31 | .094 | .163 |
| September | 28 | .437 | .270 | -- | -- | -- | 28 | .056 | .021 | 29 | .020 | .015 | 29 | .048 | .036 |
| Overall | 72 | .534 | .446 | 41 | .607 | .462 | 72 | .060 | .025 | 78 | .019 | .013 | 78 | .069 | .108 |
| Health Department | | | | | | | | | | | | | | | |
| July | 16 | .257 | .059 | 4 | .137 | .151 | 16 | .032 | .026 | 18 | .010 | .006 | 18 | .023 | .009 |
| August | 25 | .407 | .297 | 29 | .176 | .215 | 25 | .033 | .021 | 31 | .012 | .011 | 31 | .030 | .025 |
| September | 27 | .269 | .184 | 17 | .348 | .304 | 27 | .029 | .019 | 28 | .013 | .012 | 28 | .025 | .026 |
| Overall | 68 | .317 | .225 | 50 | .231 | .255 | 68 | .031 | .021 | 77 | .012 | .011 | 77 | .027 | .023 |
| Liberty Mounds | | | | | | | | | | | | | | | |
| July | 7 | .248 | .145 | | | | 7 | .008 | .004 | 12 | .003 | .003 | 12 | .024 | .021 |
| August | 25 | .231 | .204 | | | | 25 | .006 | .003 | 29 | .002 | .002 | 29 | .024 | .027 |
| September | 27 | .210 | .163 | | | | 27 | .004 | .004 | 29 | .002 | .002 | 29 | .028 | .029 |
| Overall | 59 | .223 | .178 | | | | 59 | .006 | .004 | 70 | .002 | .002 | 70 | .026 | .027 |

TABLE 4.1. MONTHLY AVERAGES AND STANDARD DEVIATIONS OF SELECTED PARAMETERS (continued)

| | % Tailpipe Emissions | | | NO, ppm | | | $NO_2$, ppm | | | $NO_x$, ppm | | | $\Sigma NMHC/NO_x$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | Mean | S.D. | N | Mean | S.D. | N | Mean | S.D. | N | Mean | S.D. | N | Mean | S.D. |
| Post Office | | | | | | | | | | | | | | | |
| July | 15 | 40 | 18 | 21 | .031 | .036 | 21 | .033 | .009 | 21 | .065 | .042 | 15 | 9.1 | 4.5 |
| August | 29 | 68 | 59 | 31 | .046 | .043 | 30 | .029 | .010 | 30 | .073 | .051 | 28 | 13.6 | 12.0 |
| September | 28 | 73 | 32 | 28 | .030 | .036 | 28 | .025 | .009 | 28 | .055 | .042 | 27 | 9.2 | 3.2 |
| Overall | 72 | 64 | 44 | 80 | .036 | .039 | 79 | .029 | .010 | 79 | .065 | .046 | 70 | 11.0 | 8.3 |
| Health Department | | | | | | | | | | | | | | | |
| July | 16 | 52 | 22 | 20 | .004 | .005 | 21 | .016 | .008 | 20 | .021 | .012 | 15 | 13.4 | 6.3 |
| August | 25 | 49 | 27 | 30 | .011 | .018 | 30 | .017 | .010 | 30 | .028 | .026 | 25 | 20.7 | 23.5 |
| September | 27 | 75 | 21 | 30 | .017 | .024 | 29 | .018 | .008 | 29 | .035 | .032 | 27 | 9.3 | 5.8 |
| Overall | 68 | 60 | 26 | 80 | .011 | .019 | 80 | .017 | .009 | 79 | .027 | .024 | 67 | 14.4 | 15.8 |
| Liberty Mounds | | | | | | | | | | | | | | | |
| July | 7 | 11 | 8 | 26 | .001 | .002 | 30 | .008 | .004 | 26 | .010 | .004 | 7 | 33.9 | 32.4 |
| August | 25 | 15 | 12 | 29 | .002 | .002 | 30 | .004 | .004 | 29 | .006 | .005 | 24 | 47.2 | 33.2 |
| September | 27 | 20 | 17 | 29 | .002 | .002 | 28 | .004 | .004 | 28 | .005 | .006 | 20 | 47.7 | 31.2 |
| Overall | 59 | 17 | 5 | 84 | .002 | .002 | 88 | .005 | .004 | 83 | .007 | .005 | 51 | 45.6 | 32.0 |

Additional figures describing the surface distribution of ozone are included in the discussion of certain case study days. On these concentration-distance plots the abscissa is linear distance to the north from Liberty Mounds. The ordinate is ozone concentration in ppm, and each symbol is the average ozone concentration for each station for the hour indicated. A solid line extends from Liberty Mounds through the city to Sperry, Vera, and finally Ochelata along a south-to-north path. The dashed line extends from the city through Skiatook and on to Wynona, two sites northwest of the city.

When meteorological conditions were appropriate, an estimate was made of the net impact of Tulsa on ozone formation downwind. The procedure employed is as follows. On days when southerly winds were present in the study area, the surface ozone concentration measured at Liberty Mounds for hours 1000 and 1100 CST was assumed to represent the background ozone influencing the Tulsa area. The surface inversion was expected to be completely destroyed between 0900 and 1000 CST by the morning's solar heating. Therefore, ozone that had been trapped above the nocturnal inversion should have begun to mix to the surface by 1000. The net impact of Tulsa emissions on ozone formation is estimated by subtracting the background ozone concentration from the maximum ozone concentration measured at a site downwind of the city.

It must be emphasized that this approach is one of several that might be considered. It is similar to that outlined in the document EPA 450/2-77-021a, Uses, Limitations, and Technical Basis of Procedures for Quantifying Relationships Between Photochemical Oxidants and Precursors. Also, several assumptions are made: (1) the background ozone at other stations in the network would have been similar to that observed at Liberty Mounds; (2) no changes occur in the ozone concentration aloft during the period 1000 up until the time of recorded ozone maxima; (3) the maximum ozone concentration measured at the downwind station(s) is representative of the maximum ozone concentration within the Tulsa plume.

## 4.2 JULY 21 THROUGH 25, 1977: CASE STUDY

### 4.2.1 Introduction

The period July 21-25 (Thursday through Monday) was chosen for case study analysis primarily because the maximum ozone concentrations at both the Post Office and Health Department on July 22 were also the maxima of the entire summer study at those sites. On July 23 the maximum ozone concentrations at the city sites were also near the summer maxima. On July 24 and 25 the meteorological conditions were similar to those of July 22 and 23, but on those days the maximum ozone concentrations measured at the city sites were not abnormally high. Differences between these days will be identified.

July 21 was included in the case study because it was a day with conditions that were representative of those most frequently observed in Tulsa during the summer of 1977. July 21, therefore, provided a data base to which the data of the days following it could be compared.

Figures that summarize the meteorological and chemical data for the case study period are presented on the following pages. Figures 4.1a through 4.1g are the National Weather Service 0700 EST surface weather maps for the United States for July 20 through 26. Figures 4.2 and 4.3 show the synoptic and local (mesoscale) backward air parcel trajectories for the case study days. Figures 4.4a through 4.4e are the forward trajectories of the urban air parcel for each day of the case study. The diurnal variations in temperature and solar radiation during the case study are shown in Figures 4.5 and 4.6, respectively. Figure 4.7 illustrates the diurnal profiles for NO and $NO_2$ at the two city sites. Figure 4.8 illustrates the diurnal profiles for ozone at each site in the network.

Values for the individual hours of data for all the meteorological and chemical data measured during the case study can be found in Volume II of this report.

### 4.2.2 Overview of the Case Study Period

On the 0700 EST (0600 CST) surface weather map for July 21 (Figure 4.1), a cold front was shown moving through the panhandle region of Oklahoma. An area of high pressure which was centered over the southeastern States produced southerly winds in the Tulsa area until 1600 CST. Following 1600 the front began to influence the Tulsa area and the winds began to shift to westerly. The synoptic-scale trajectories (Figure 4.2) indicate steady flow from the south for the 48 hours preceding the air parcel arrival times (either 0600 or 1600 CST) in Tulsa. The local (mesoscale) back trajectories

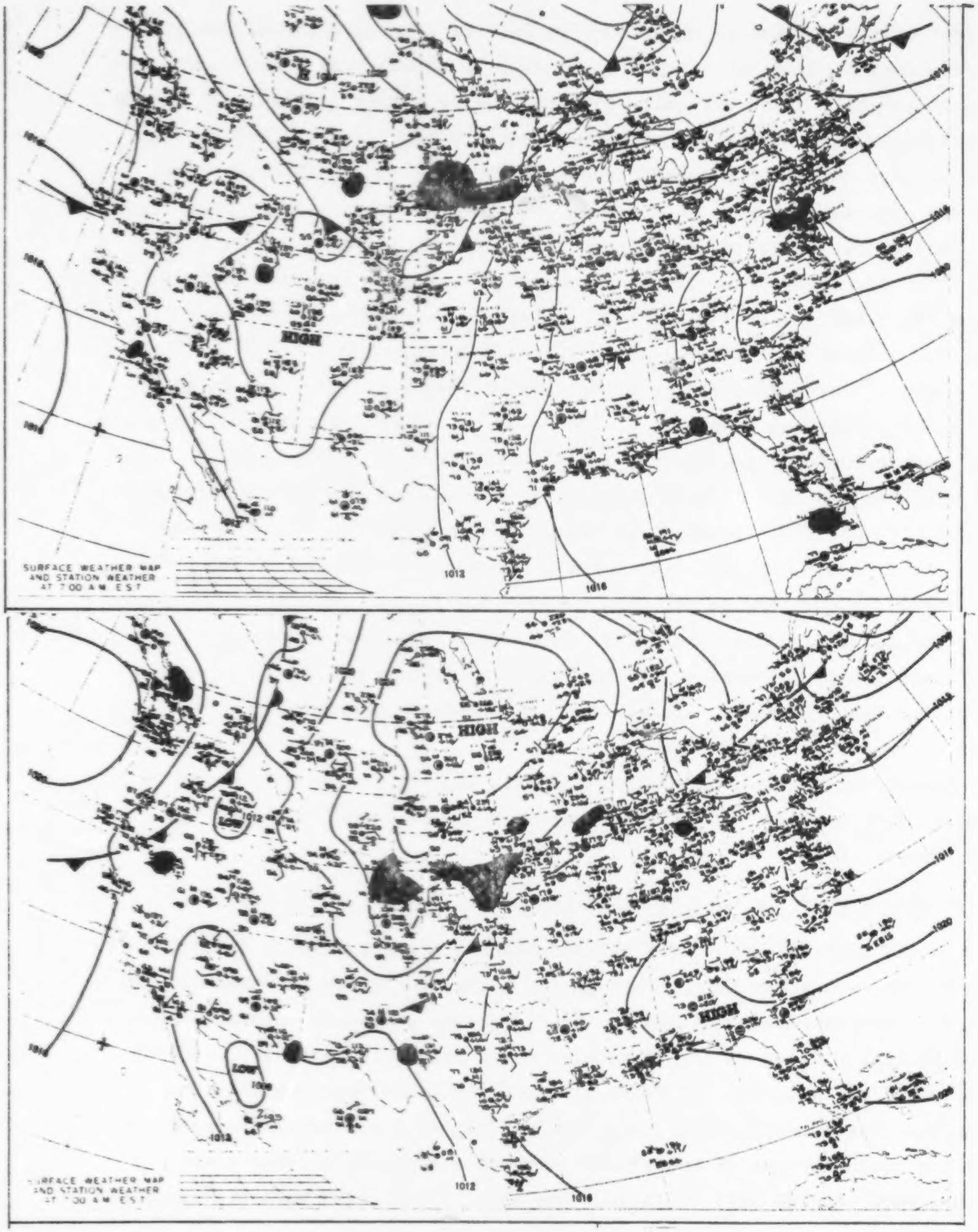
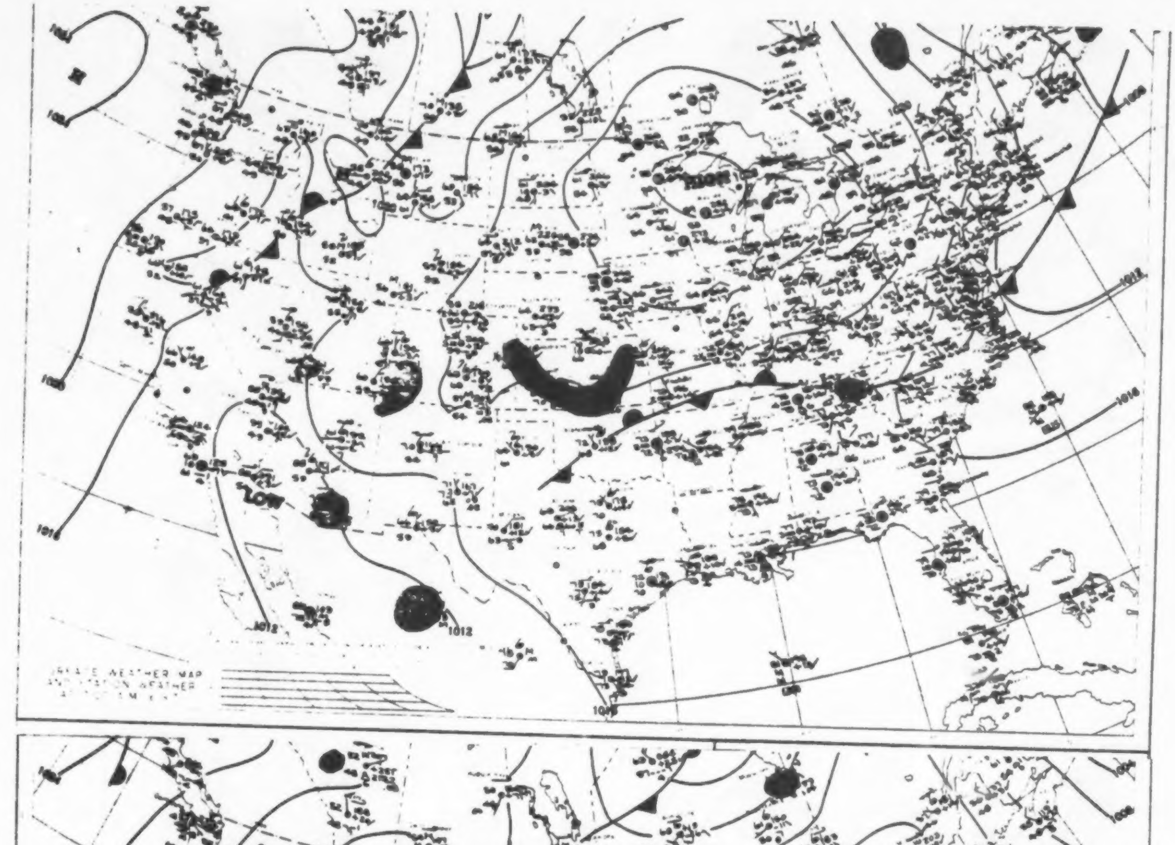
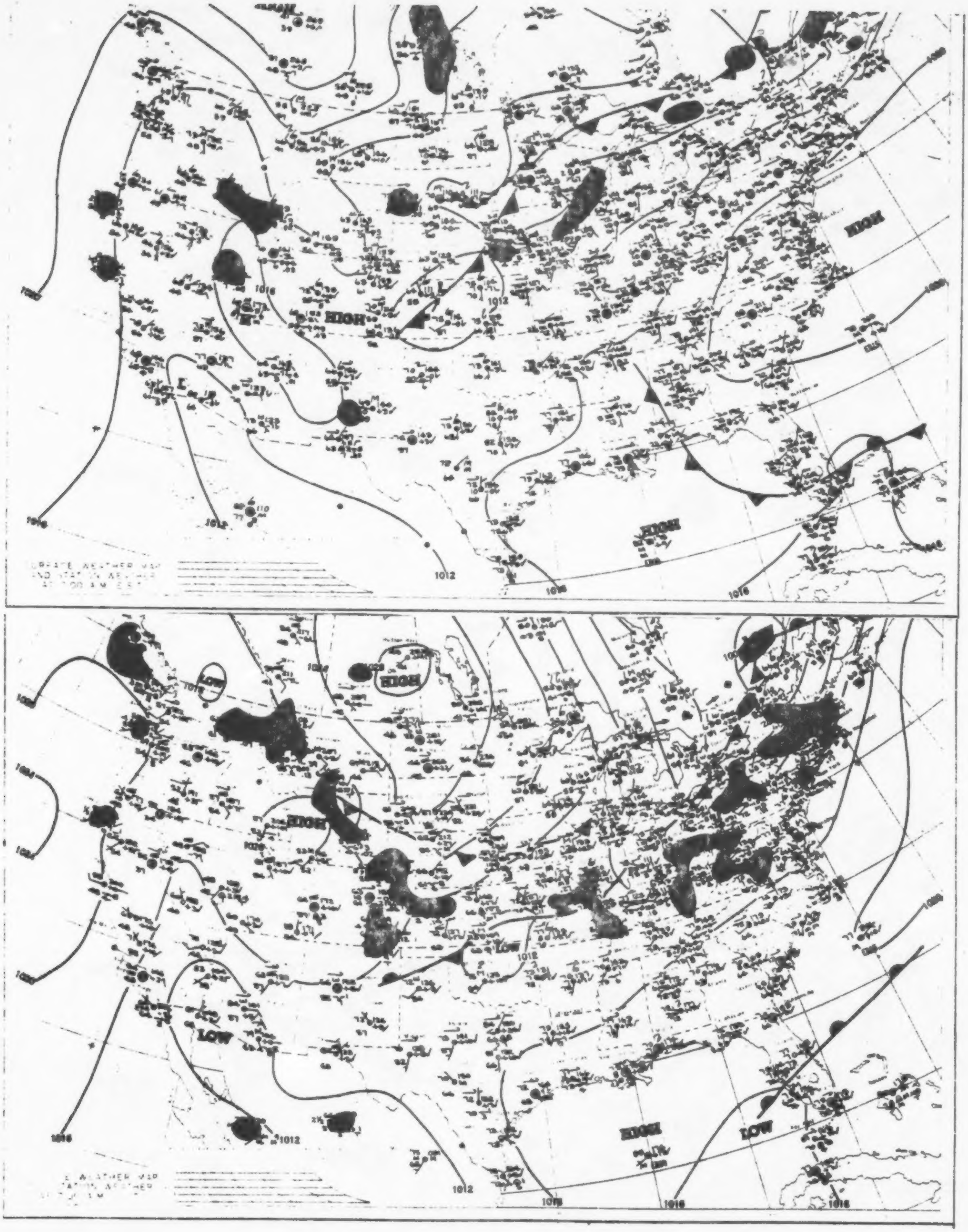

HIGH
1012
1016
SURFACE WEATHER MAP
AND STATION WEATHER
AT 7:00 A.M. E.S.T.
HIGH
LOW
LOW
HIGH
1012
1016
1020
SURFACE WEATHER MAP
AND STATION WEATHER
AT 7:00 A.M. E.S.T.

Figure 4.1a and 4.1b. United States surface weather maps for July 20 and July 21, 1977.


SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.
HIGH
LOW
LOW
1012
1016
1020
LOW
LOW
HIGH
1012
1016
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.

Figures 4.1c and 4.1d. United States surface weather maps for July 22 and July 23, 1977.



HIGH
HIGH
HIGH
1012
1016
1020
HIGH
LOW
HIGH
LOW
HIGH
LOW
1012
1016

Figures 4.1e and 4.1f. United States surface weather maps for July 24 and July 25, 1977.

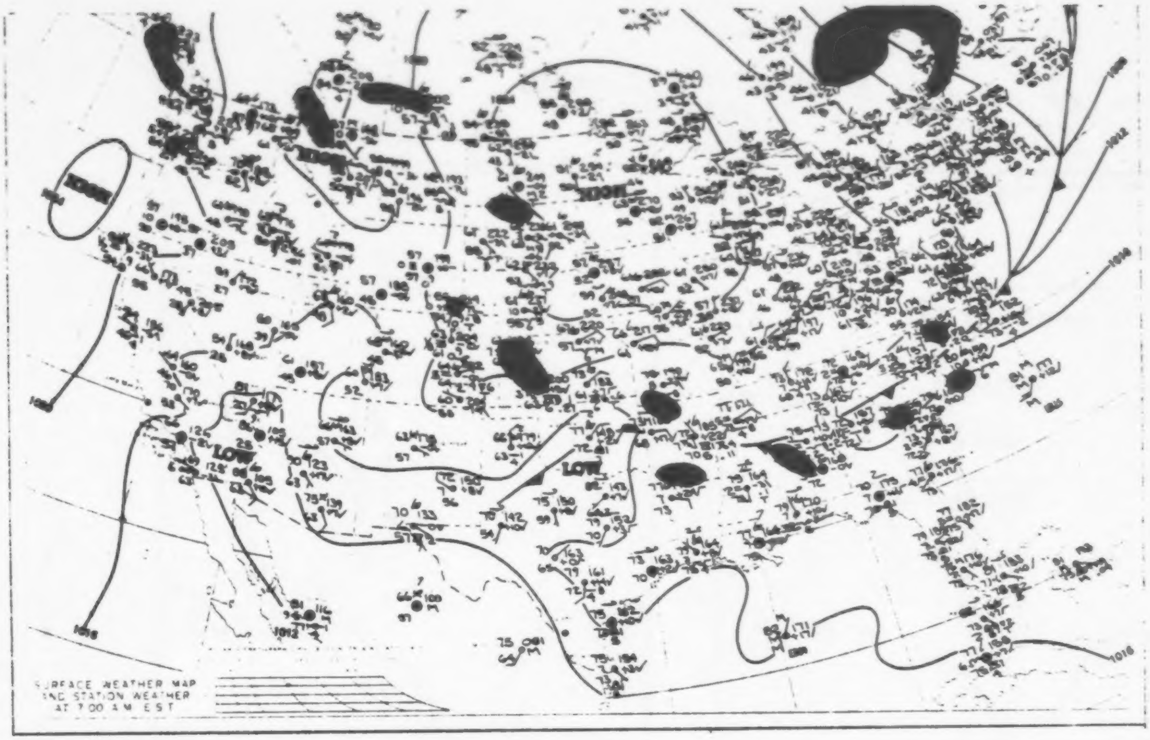

SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.
LOW
LOW
1016
1012
1016
1016

Figure 4.1g. United States surface weather map for July 26, 1977.

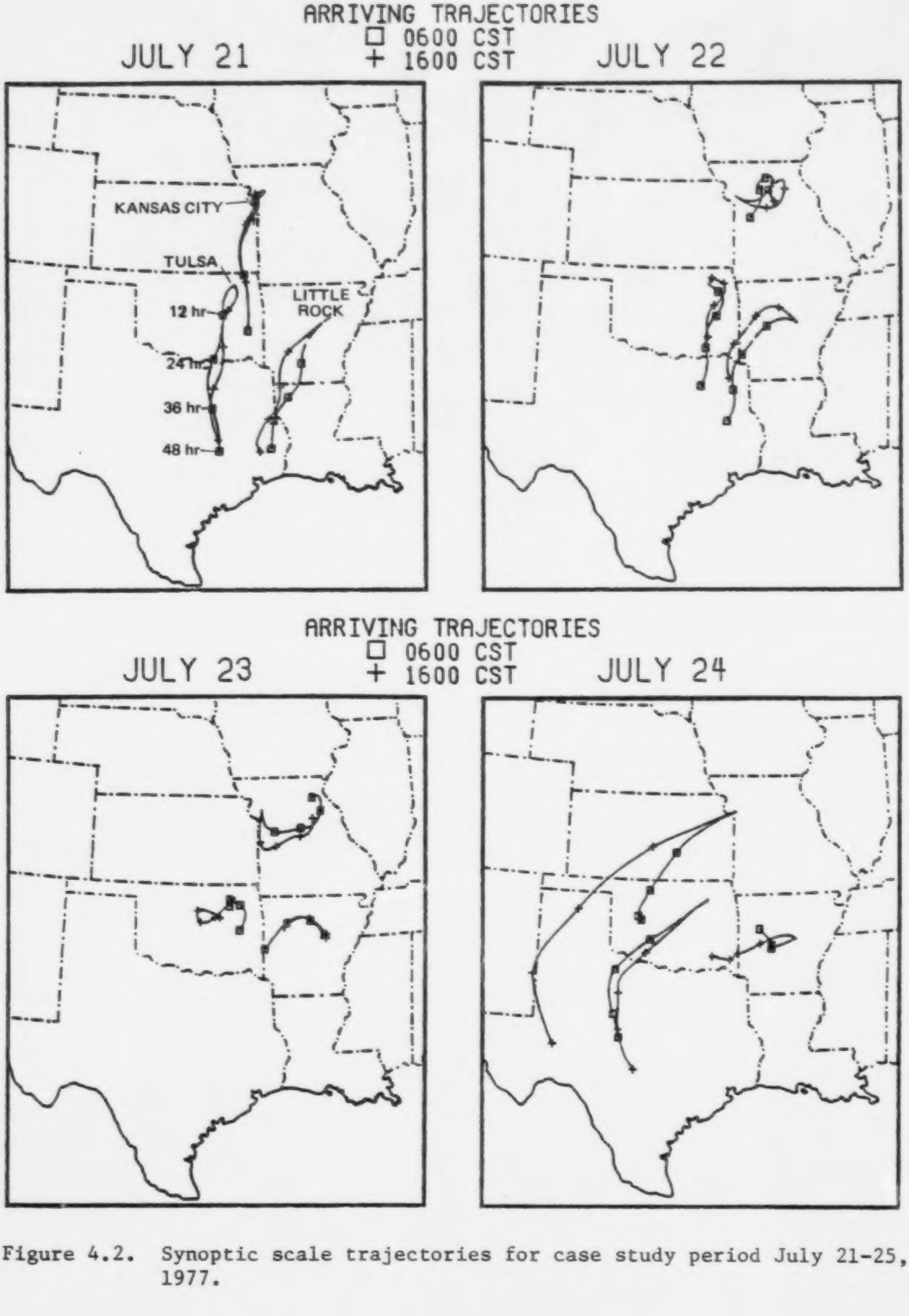

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
JULY 21
JULY 22
KANSAS CITY
TULSA
12 hr
24 hr
36 hr
48 hr
LITTLE ROCK
ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
JULY 23
JULY 24

Figure 4.2. Synoptic scale trajectories for case study period July 21-25, 1977.

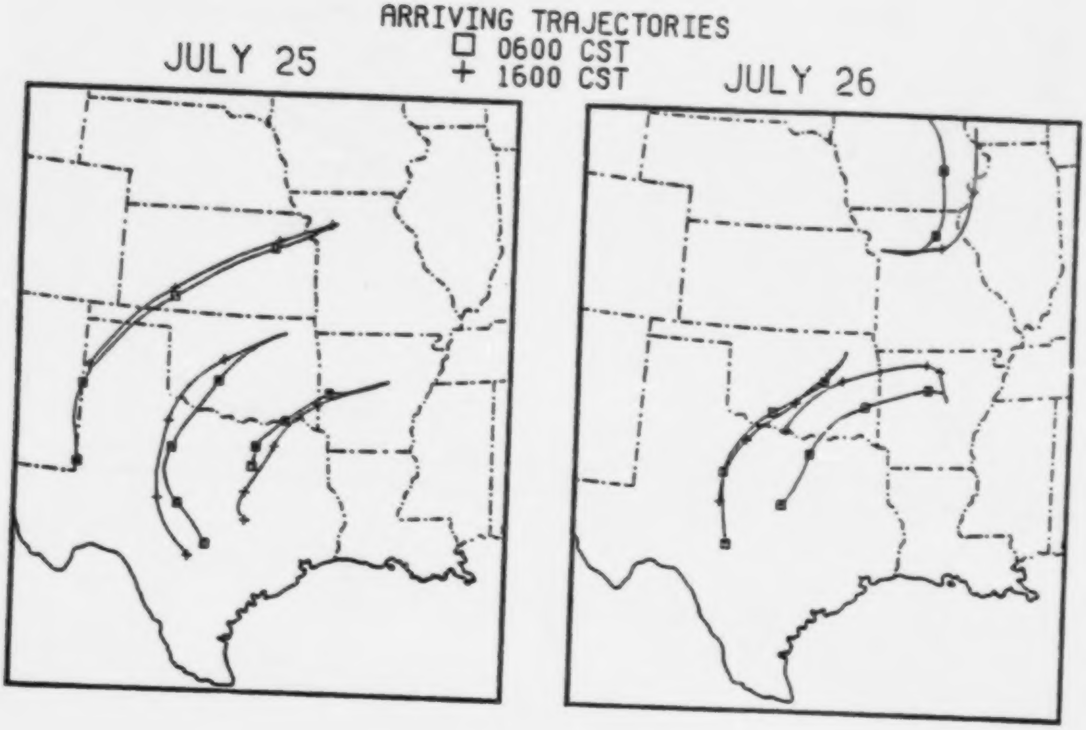

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
JULY 25
JULY 26

Figure 4.2. Synoptic scale trajectories for case study period July 21-25, 1977. (continued).

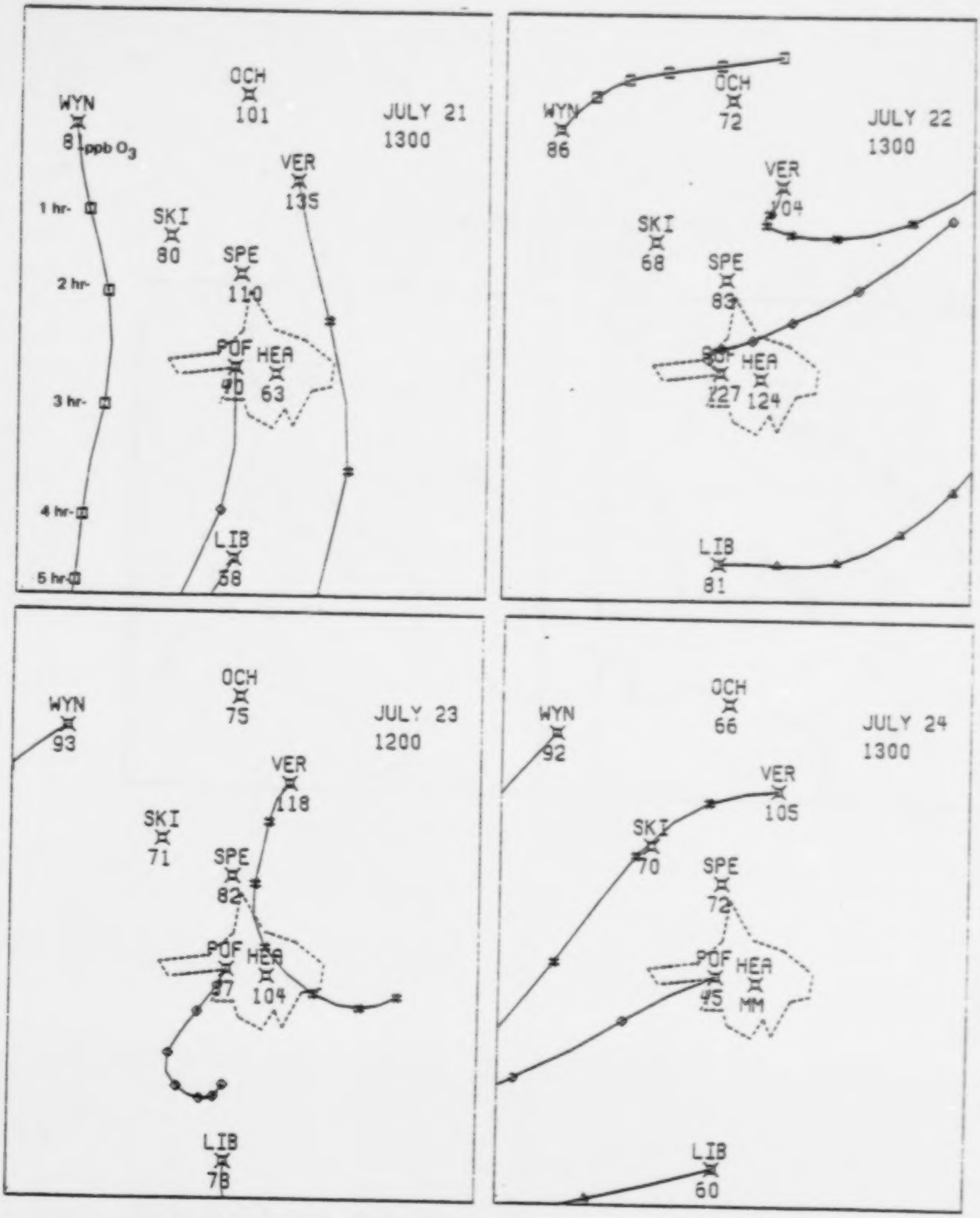

OCH
101
WYN
8 ppb $O_3$
JULY 21
1300
VER
135
1 hr-
SKI
80
SPE
110
2 hr-
POF
40
HEA
63
3 hr-
4 hr-
LIB
58
5 hr-
OCH
72
WYN
86
JULY 22
1300
VER
104
SKI
68
SPE
83
POF
127
HEA
124
LIB
81
OCH
75
WYN
93
JULY 23
1200
VER
118
SKI
71
SPE
82
POF
97
HEA
104
LIB
78
OCH
66
WYN
92
JULY 24
1300
VER
105
SKI
70
SPE
72
POF
45
HEA
MM
LIB
60

Figure 4.3. Mesoscale trajectories for the case study period July 21-25, 1977.

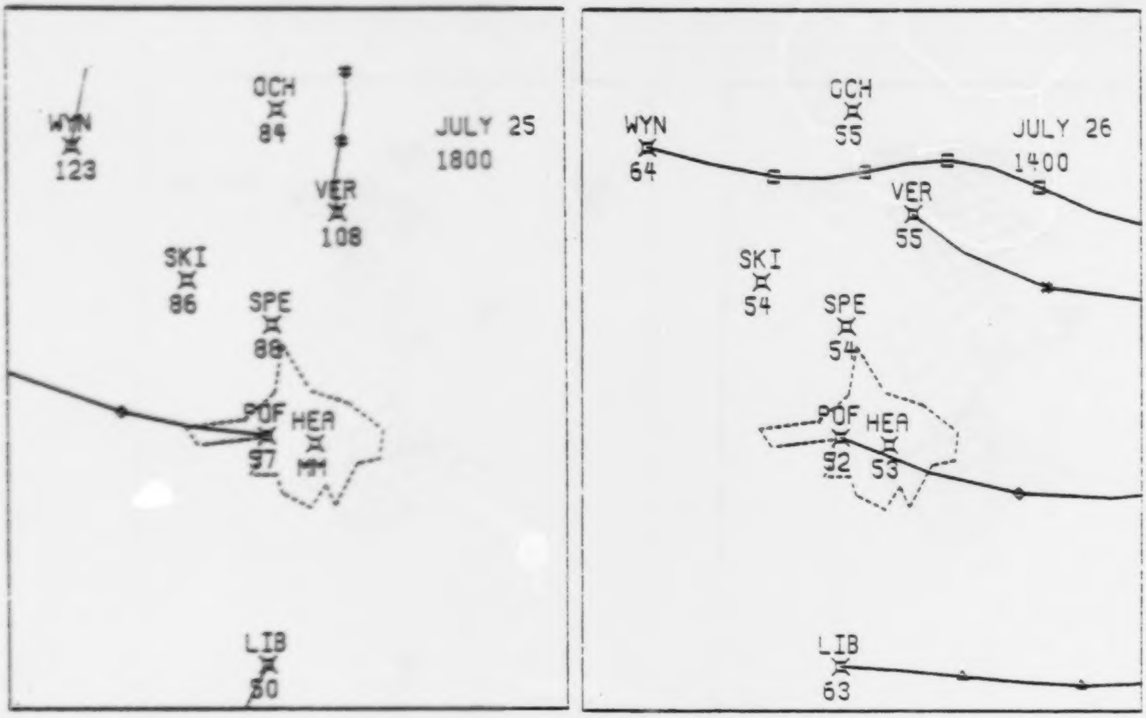

OCH
84
WYN
123
JULY 25
1800
VER
108
SKI
86
SPE
88
POF
97
HEA
MM
LIB
50
OCH
55
WYN
64
JULY 26
1400
VER
55
SKI
54
SPE
54
POF
92
HEA
53
LIB
63

**Figure 4.3.** Mesoscale (local) trajectories for case study period July 21-25, 1977. (continued).

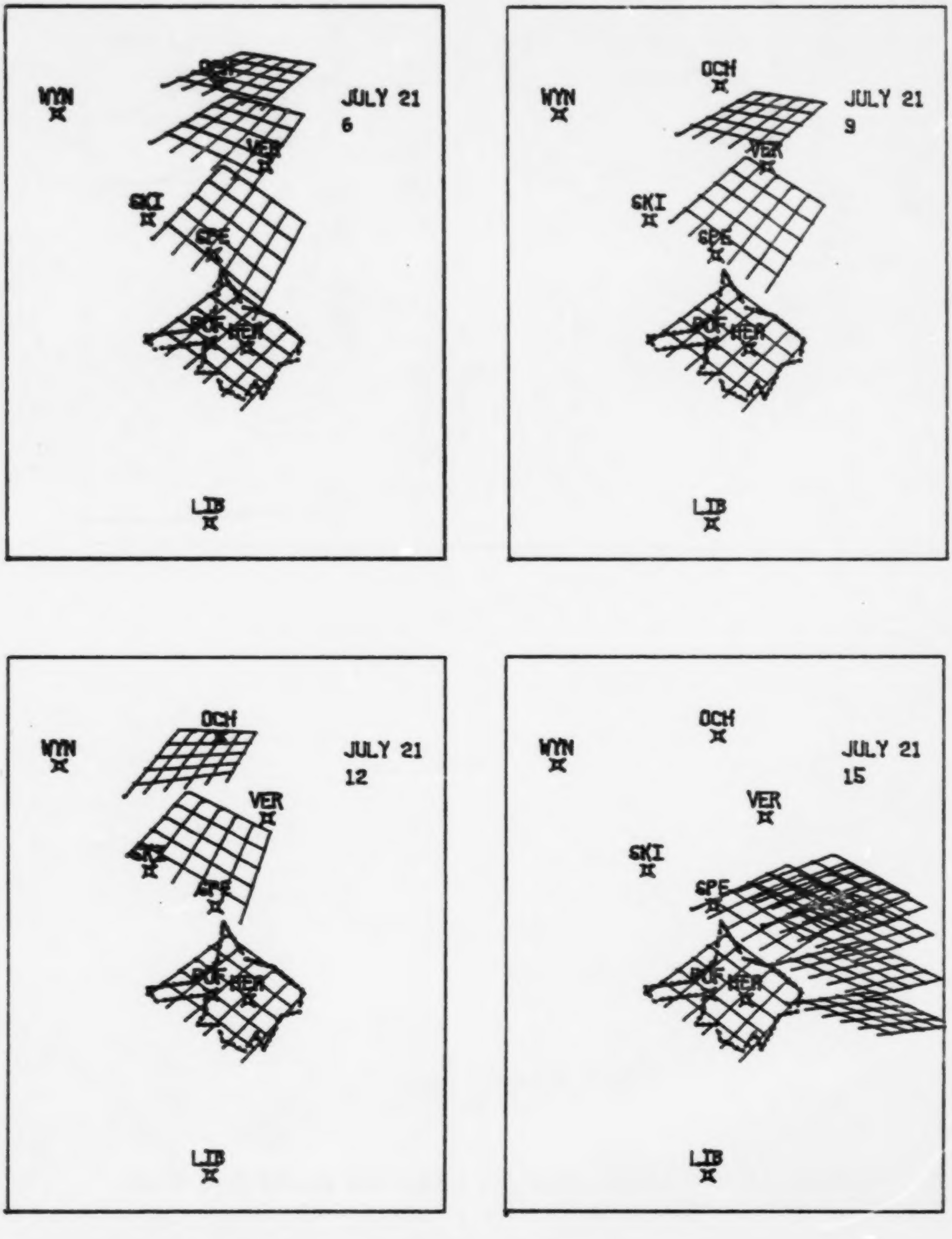

WYN
OCH
VER
SKI
SPE
PUF
HER
LIB
JULY 21
6
JULY 21
9
JULY 21
12
JULY 21
15

Figure 4.4a. Forward air parcel trajectories for July 21, 1977.

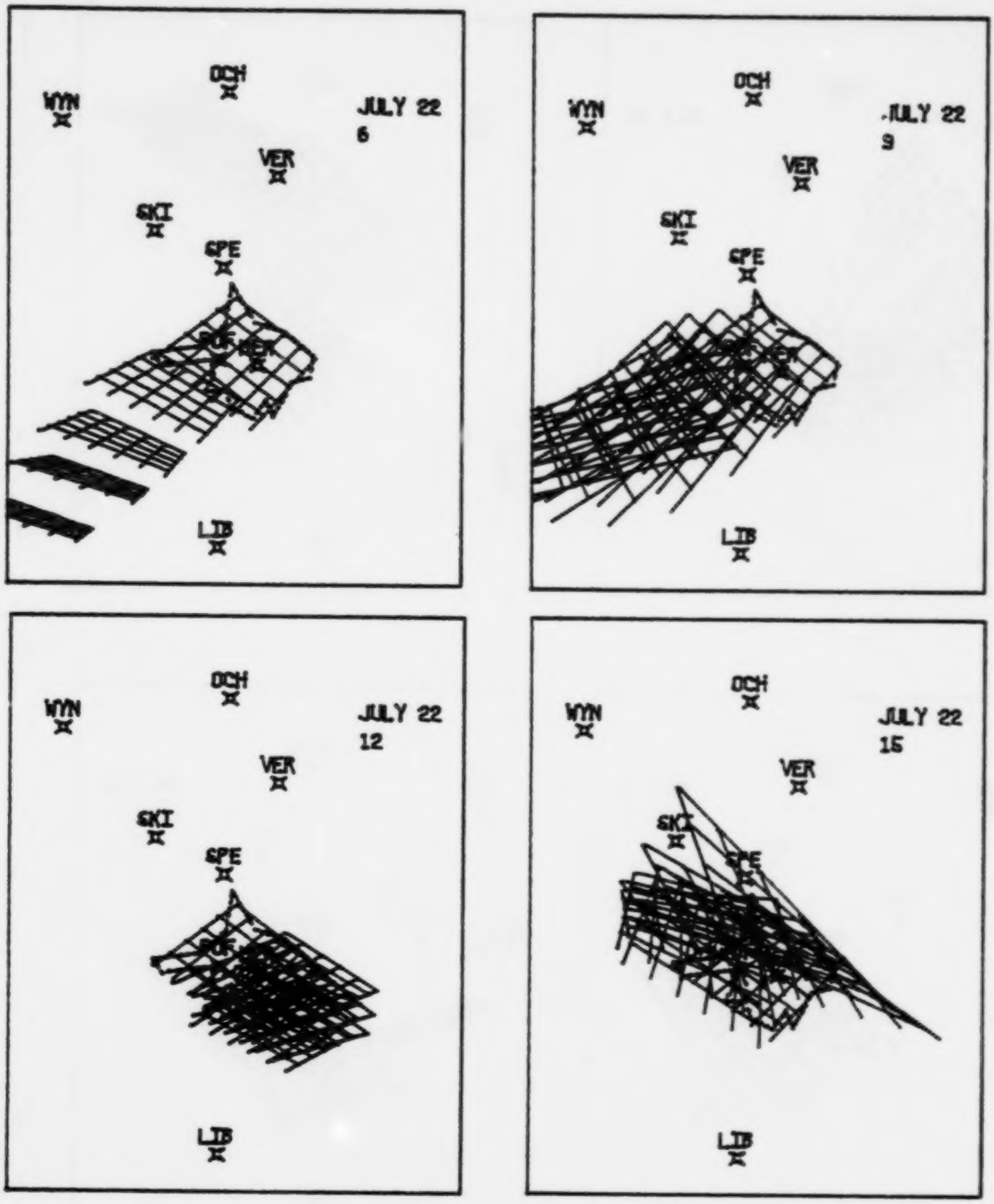

WYN
OCH
JULY 22
6
VER
SKI
SPE
LIB
WYN
OCH
JULY 22
9
VER
SKI
SPE
LIB
WYN
OCH
JULY 22
12
VER
SKI
SPE
LIB
WYN
OCH
JULY 22
15
VER
SKI
SPE
LIB

Figure 4.4b. Forward air parcel trajectories for July 22, 1977.

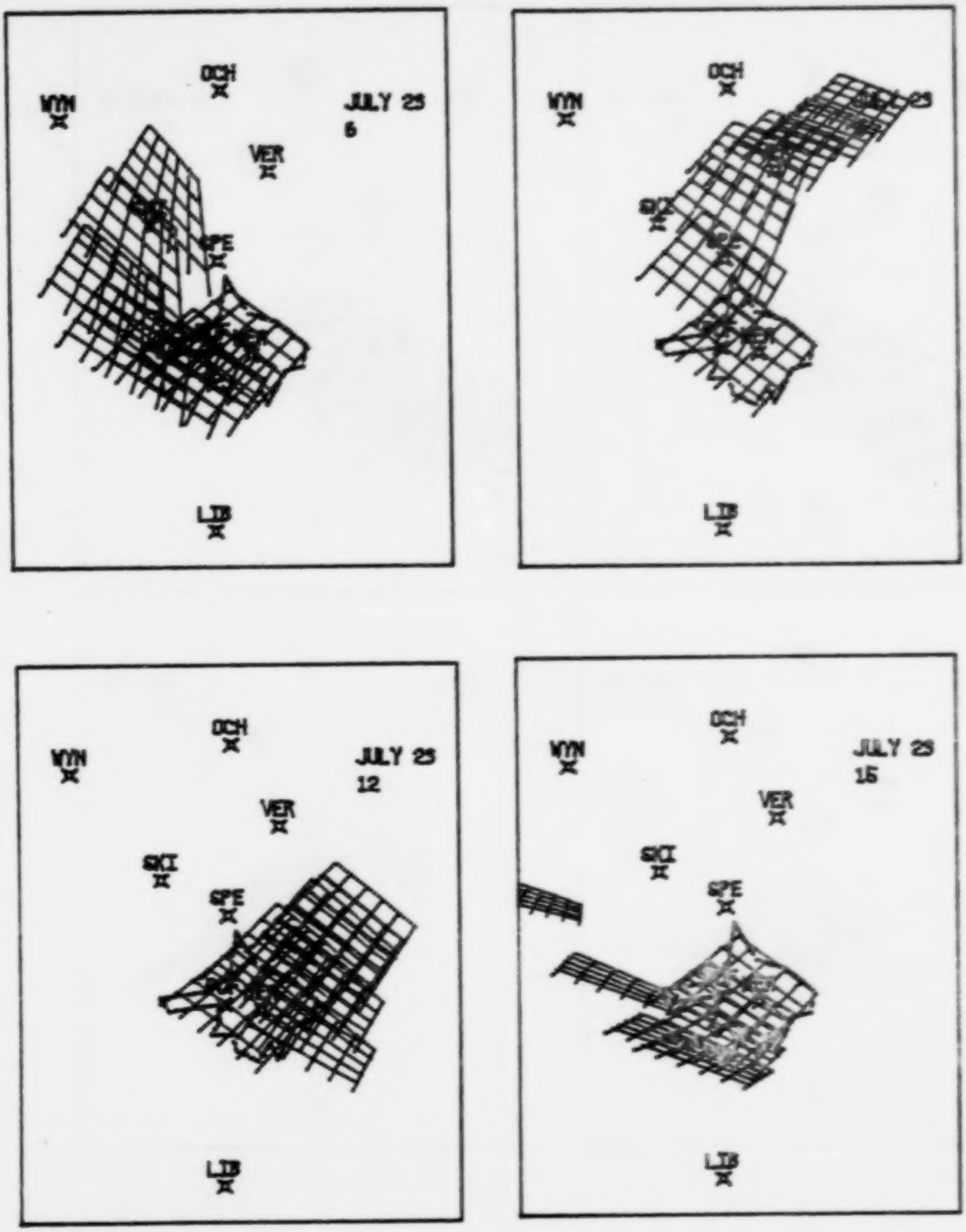


Figure 4.4c. Forward air parcel trajectories for July 23 1977.

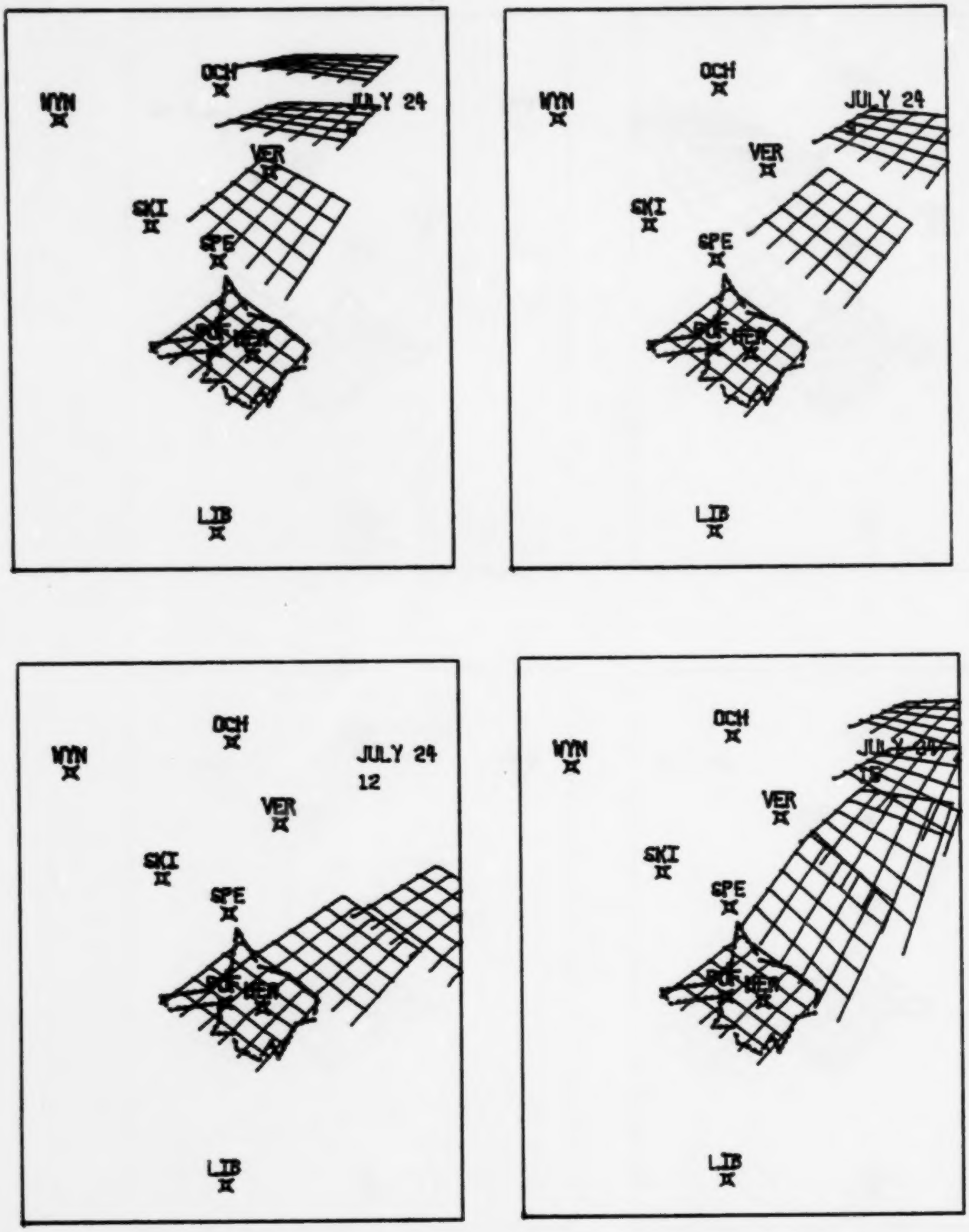

OCH
WYN
JULY 24
VER
SKI
SPE
LIB
OCH
WYN
JULY 24
VER
SKI
SPE
LIB
OCH
WYN
JULY 24
12
VER
SKI
SPE
LIB
OCH
WYN
VER
SKI
SPE
LIB

Figure 4.4d. Forward air parcel trajectories for July 24, 1977.

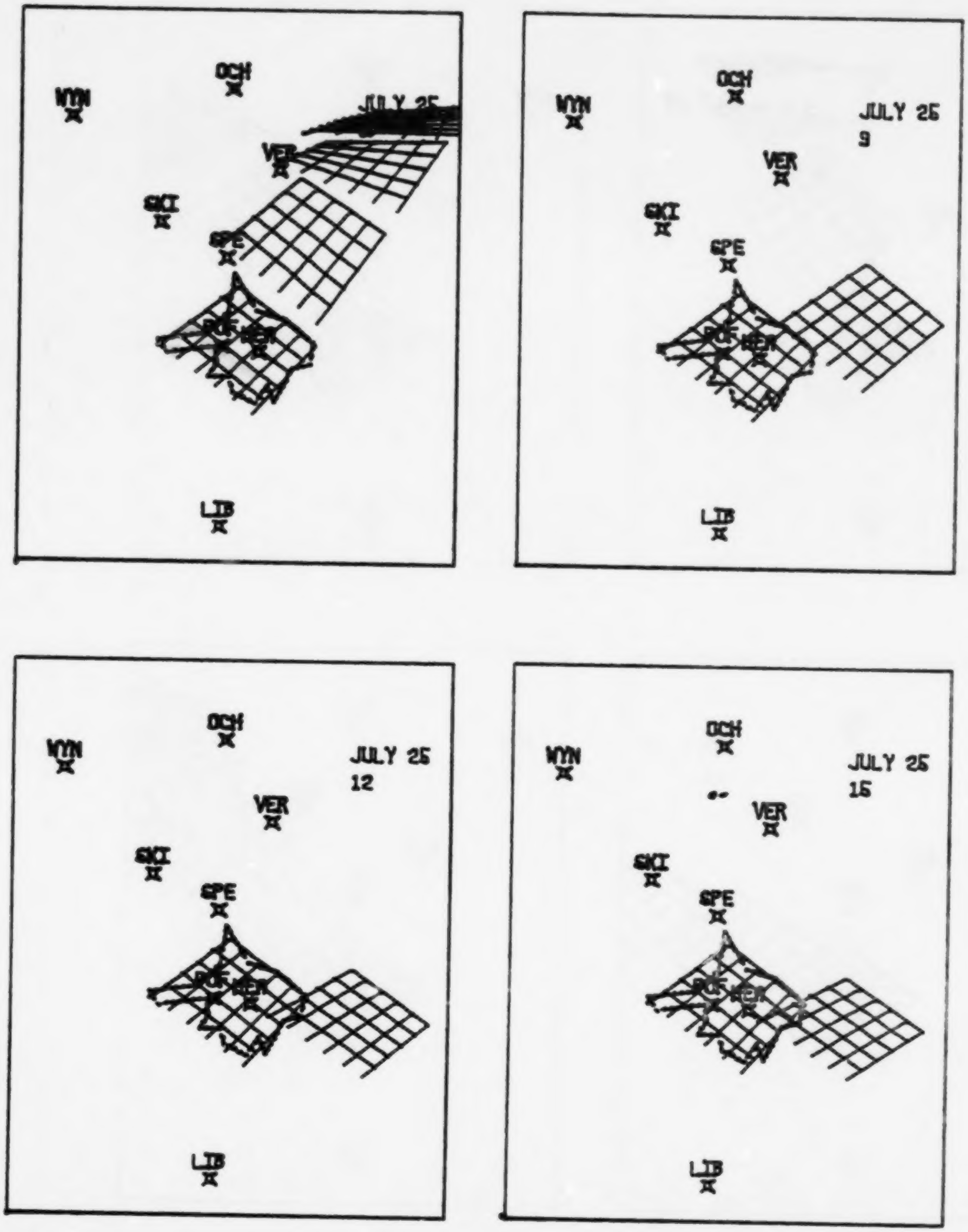


Figure 4.4e. Forward air parcel trajectories for July 25, 1977.

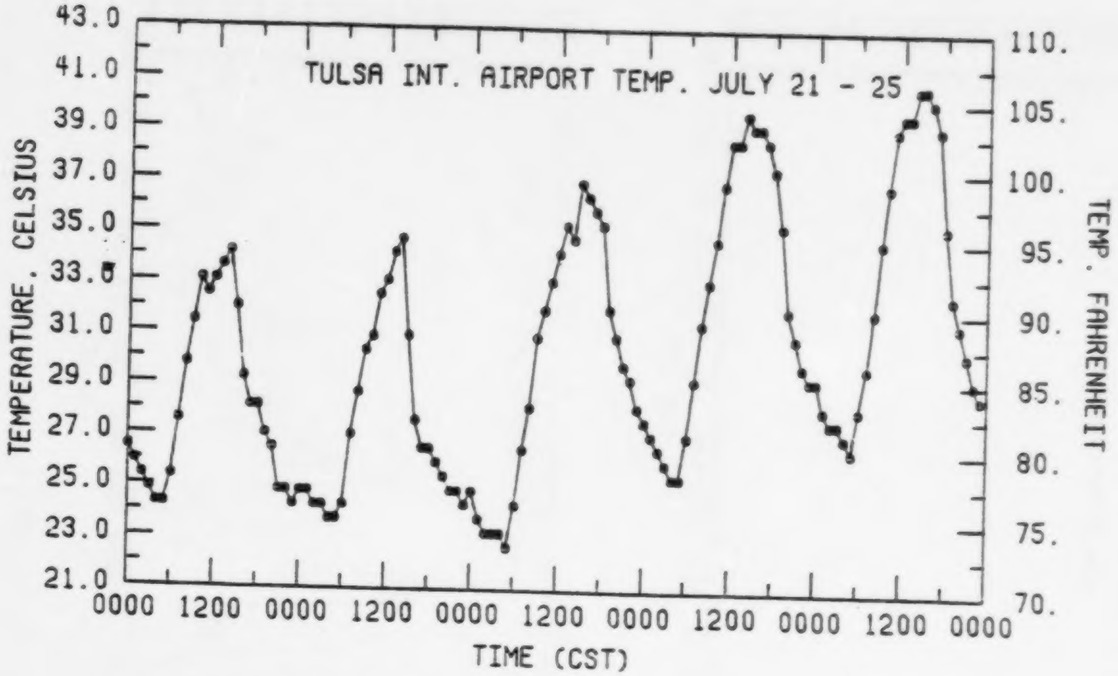


Figure 4.5. Diurnal variation of temperature for the period July 21-25, 1977.

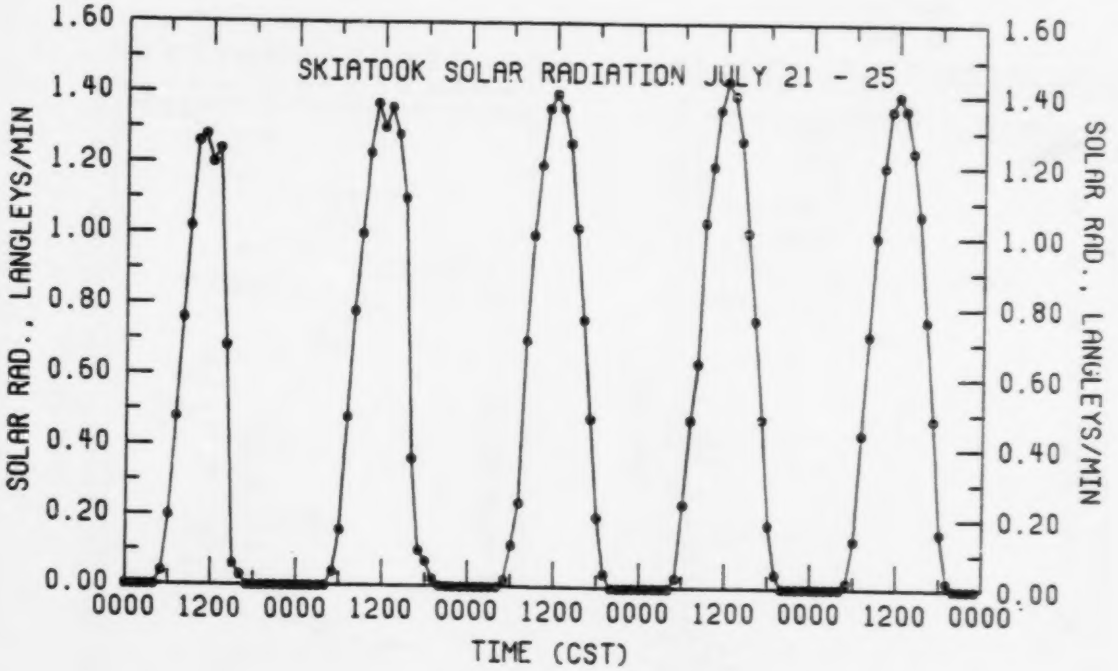


Figure 4.6. Diurnal variation of solar radiation for the period July 21-25, 1977.

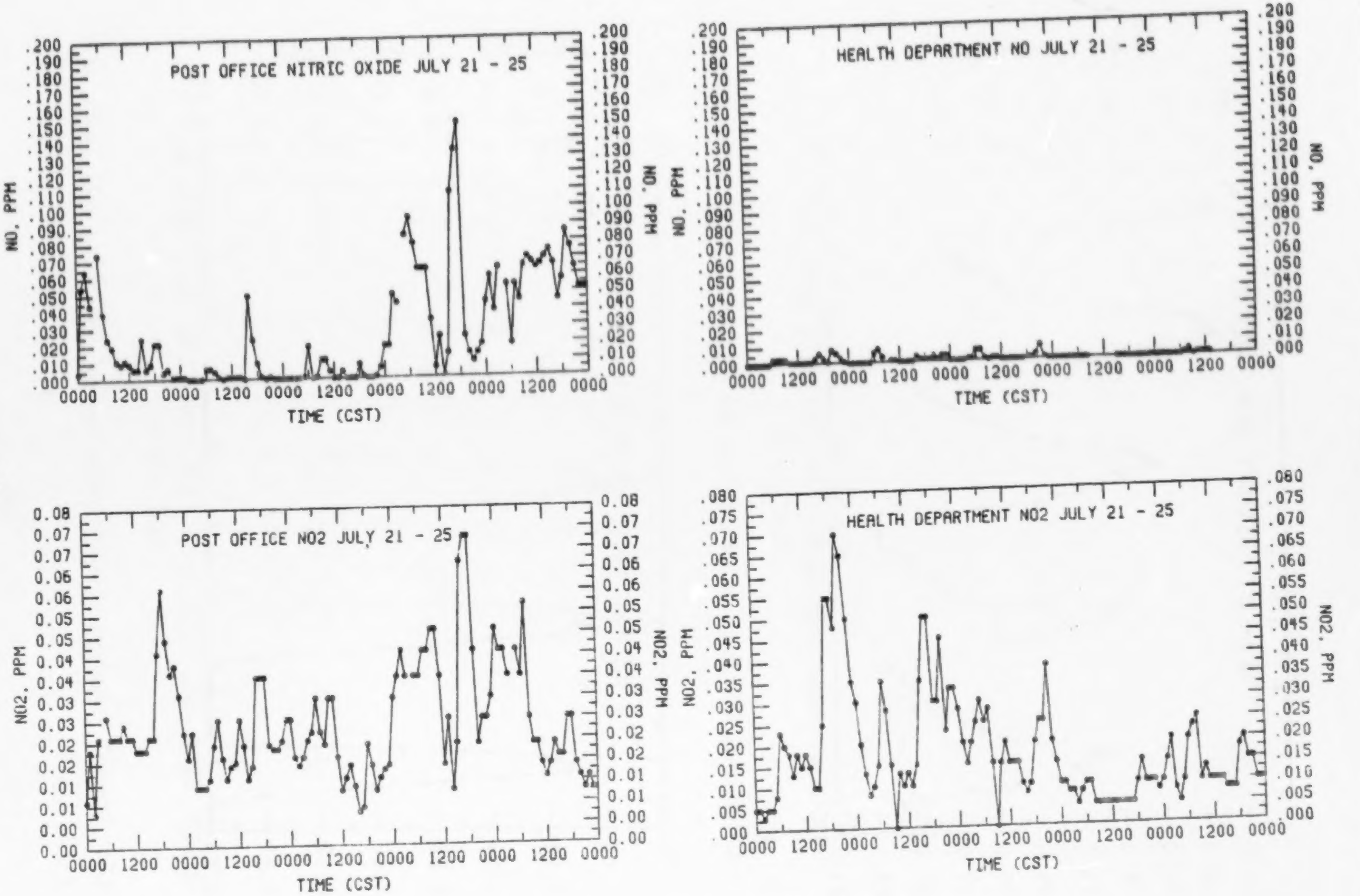


Figure 4.7. Diurnal variations of NO and $NO_2$ for the period July 21-25, 1977.

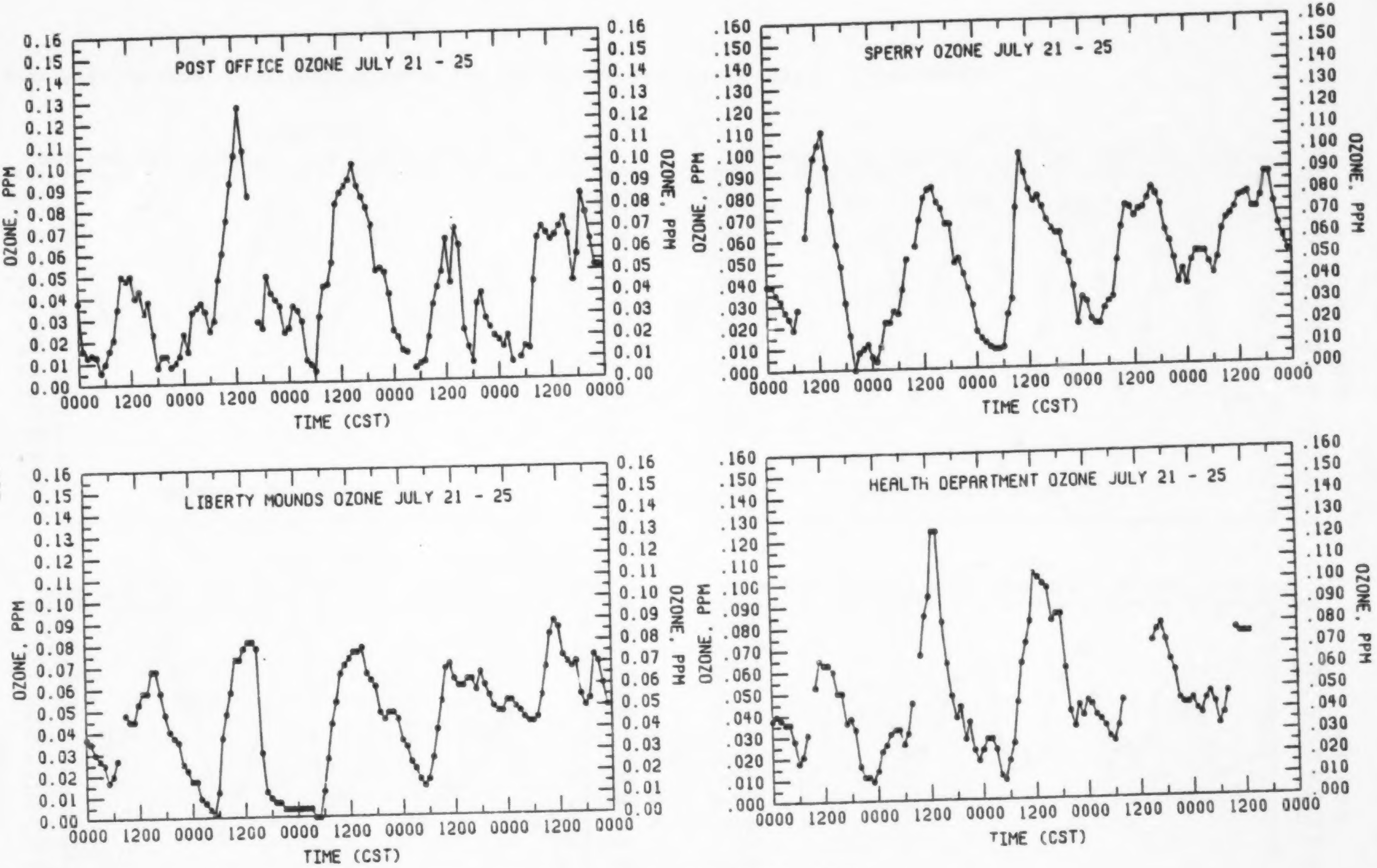


Figure 4.8. Diurnal variation of ozone for the period July 21-25, 1977.

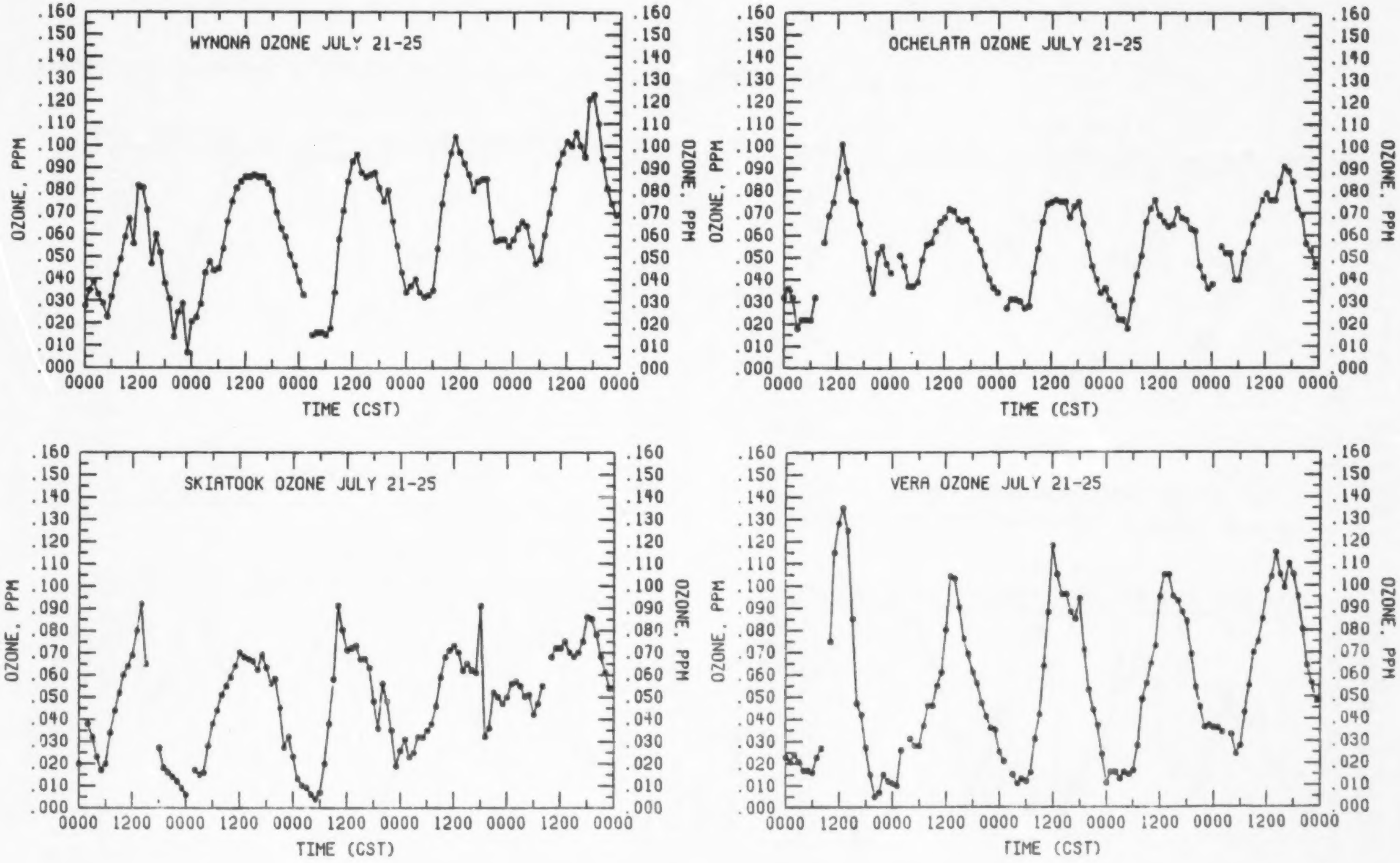


Figure 4.8. Diurnal variation of ozone for the period July 21-25, 1977. (continued).

(Figure 4.3), calculated for air parcel arrival at 1300, also show steady southerly winds. In Figure 4.4a, forward trajectories of the Tulsa urban air parcel are shown for air leaving Tulsa at four different times during the day. The first three of these forward trajectories, for air leaving Tulsa at 0600, 0900, and 1200, all show steady advection of the Tulsa urban air to the north. The air leaving Tulsa at 1500, however, moved first to the northeast and then drifted slowly back to the south. This was due to the influence of the cold front, which disturbed the steady southerly winds.

The solar radiation measured at Skiatook reached a maximum near 1.3 langleys per minute at 1100 but by 1500 it had decreased substantially due to the arrival of a cloud cover associated with the approaching frontal system. The maximum ozone concentration in the network of 0.135 ppm occurred at Vera at 1300, and the influence of the frontal system probably did not offset the maximum ozone significantly.

The concentrations of selected hydrocarbons, oxides of nitrogen, and some important ratios, measured during the 6-9 a.m. CDT time period for the days of the case study period, are listed in Table 4.2. The concentrations of nonmethane hydrocarbons (NMHC) of 0.327 ppmC and $NO_x$ of 0.073 ppm that were measured at the Post Office were higher than the concentrations that were measured at both the Health Department and Liberty Mounds. Under the influence of the southerly winds, morning emissions from the refinery area in Tulsa and morning traffic emissions produced concentrations at the Post Office that were higher than at the Health Department. Actually, the concentration of NMHC at the Post Office was less than the July average of 0.430 ppmC. At the Health Department and Liberty Mounds the concentrations of NMHC of 0.239 and 0.240 ppmC, respectively, were very close to the average concentrations measured at those stations during July. Good ventilation, resulting from the steady wind flow, probably caused dispersal of the refinery emissions to some degree before the air reached the Post Office Station. After the 6-9 CDT period, the total $NO_x$ decreased at both the Post Office and Health Department stations until the evening traffic period began around 1500 to 1600 CST.

By the morning of July 22 the front had moved directly into the Tulsa area and had become stationary (Figure 4.1). The front had drifted slowly

TABLE 4.2. 0500 TO 0800 CST AVERAGE CONCENTRATIONS OF SELECTED HYDROCARBONS AND OXIDES OF NITROGEN, AND DISTRIBUTIONS FOR JULY 21 THROUGH JULY 25, 1977

|  | ΣNMHC ppmC | NMHC Beckman ppmC | ΣAlkenes ppbC | Acetylene ppbC | n-Butane ppbC | % tailpipe emissions | NO ppm | $NO_2$ ppm | $NO_x$ ppm | ΣNMHC/$NO_x$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Post Office |  |  |  |  |  |  |  |  |  |  |
| July 21 | 0.327 | 0.36 | 41.2 | 9.6 | 41.6 | 45 | 0.046 | 0.028 | 0.073 | 4.5 |
| July 22 | 0.298 | 0.34 | 43.6 | 10.4 | 24.4 | 54 | 0.004 | 0.023 | 0.027 | 11.1 |
| July 23 | 0.421 | 0.62 | 44.1 | 11.4 | 34.0 | 42 | 0.007 | 0.030 | 0.036 | 11.7 |
| July 24 | 0.528 | 0.35 | 48.6 | 2.8 | 94.4 | 8 | 0.086 | 0.042 | 0.128 | 4.1 |
| July 25 | 0.687 | 0.87 | 61.2 | 11.4 | 118.0 | 26 | 0.019 | 0.048 | 0.067 | 10.3 |
| Health Department |  |  |  |  |  |  |  |  |  |  |
| July 21 | 0.239 | -- | 17.7 | 5.6 | 15.6 | 36 | 0.002 | 0.017 | 0.019 | 12.6 |
| July 22 | 0.251 | -- | 29.3 | 13.2 | 26.0 | 81 | 0.005 | 0.026 | 0.030 | 8.4 |
| July 23 | 0.335 | -- | 32.6 | 13.0 | 28.4 | 60 | 0.004 | 0.028 | 0.032 | 10.5 |
| July 24 | 0.176 | -- | 18.3 | 2.5 | 18.4 | 22 | 0.000 | 0.009 | 0.009 | 19.5 |
| July 25 | 0.270 | 0.05 | 17.1 | 5.2 | 32.4 | 30 | 0.000 | 0.018 | 0.018 | 15.0 |
| Liberty Mounds |  |  |  |  |  |  |  |  |  |  |
| July 21 | 0.240 | -- | 8.1 | 1.0 | 22.0 | 6 | 0.004 | 0.008 | 0.012 | 20.0 |
| July 22 | 0.536 | -- | 13.0 | 1.4 | 78.0 | 4 | 0.005 | 0.013 | 0.018 | 29.8 |
| July 23 | 0.327 | -- | 12.5 | 3.6 | 46.8 | 17 | 0.002 | 0.007 | 0.008 | 40.9 |
| July 24 | -- | -- | -- | -- | -- | -- | 0.003 | 0.004 | 0.007 | -- |
| July 25 | -- | -- | -- | -- | -- | -- | 0.004 | 0.003 | 0.007 | -- |

to the south by July 23 but still influenced the winds in the Tulsa area. The synoptic-scale trajectories for both July 22 and 23 (Figure 4.2) indicate stagnation with very little large-scale air motion in and around Tulsa. Both types of local-scale trajectories for July 22 (Figures 4.3 and 4.4) indicate that light easterly winds were present in Tulsa early in the day, but that during the latter part of the morning air stagnation occurred. The lack of ventilation resulted in the accumulation of ozone precursors in Tulsa. These meteorological conditions eventually resulted in the highest hourly ozone concentrations of the entire summer at both city stations.

The early morning precursor concentrations were relatively low at both city stations, but a concentration of NMHC of 0.536 ppmC was measured at Liberty Mounds. That concentration was nearly double the July average at that site. There was a very low contribution to the total NMHC from automobile emissions, however, and the high morning concentrations of NMHC at Liberty Mounds may have been largely due to sources associated with small oil operations south of Tulsa.

The local trajectories for July 23 (Figure 4.4) indicate that southerly winds were active in transporting Tulsa emissions to the north during the late morning hours, but that stagnation developed during the afternoon. Ozone concentrations in excess of 0.100 ppm were measured at the city stations on July 23; however, the network maximum of 0.118 ppm was measured at Vera at 1200.

On July 23 the morning NMHC concentration at the Post Office station was near the July average, while at both the Health Department and Liberty Mounds, higher than average concentrations were measured. Local ground level winds indicate that during the early morning hours air was moving to Tulsa from the east, and such winds were often seen to contribute to higher than average NMHC concentrations at the Health Department and Liberty Mounds.

Despite the continued influence of the frontal activity on local winds in Tulsa on July 22 and 23, there was very little cloud cover associated with the front on those days other than scattered thundershowers. The diurnal plot of solar radiation is shown in Figure 4.6, and maxima of solar radiation near 1.4 langleys per minute were reached on both days. However, on July 22 there was 0.18 inches of precipitation measured at the Tulsa

International Airport during hour 1600 and radar depiction maps show towering cumulus clouds with tops at altitudes between 13,800 m (45,000 ft) and 15,000 m (50,000 ft) in the Tulsa area. The solar radiation did drop off during 1600 and 1700 at Skiatook, but this was well after the ozone maximum was measured.

On July 24 the front that had influenced Tulsa on July 22 and 23 moved out of the area. Another cold front was approaching Oklahoma from the northwest and by July 25 it had become stationary over the northwestern part of Oklahoma (Figure 4.1). The synoptic trajectories for July 24 and 25 (Figure 4.2) show southwesterly winds typical of conditions preceding frontal activity in the midwestern States.

The local trajectories also show southwesterly winds throughout July 24 in the Tulsa area (Figures 4.3 and 4.4). Late in the day on July 25, the front began influencing the local weather in Tulsa and a wind shift was apparent in the local-scale back trajectories (Figure 4.3). The forward trajectories for July 25 (Figure 4.4) show northeasterly and easterly transport. The solar radiation reached maxima in excess of 1.4 langleys per minute on both days (Figure 4.6), and maximum temperatures were greater than 39° C (102° F) on both days.

Morning precursor concentrations were greater than the July average at the Post Office on both July 24 and 25, although low molecular weight alkanes were primarily responsible for the high concentrations of total NMHC. On July 24, 0.128 ppm of $NO_x$ was measured during the 6-9 a.m. CDT period at the Post Office, which was nearly double the July average. The refinery complex in the southwestern part of Tulsa was a strong influence on measurements made at the Post Office station as southwesterly winds persisted during the day. The maximum ozone concentrations were measured at Vera and Wynona on July 24 and 25, respectively. The local trajectories indicate that Tulsa urban emissions did not influence Wynona directly on July 25; it is not clear where that ozone had its source.

### 4.2.3 Analysis of July 21, 1977

The meteorological conditions in the Tulsa area on July 21 were representative of the conditions that most frequently influenced Tulsa during the summer of 1977. A weak high-pressure area that was centered over northern

Florida on the 0700 EST weather map (Figure 4.1b) produced southerly winds in Tulsa on July 21. A cold front was approaching Oklahoma and it extended through the panhandle regions of Texas and Oklahoma at 0700 EST on July 21. The onset of cloudiness, which reduced the solar radiation (Figure 4.6), and a shift in winds from southerly to westerly beginning in midafternoon indicated the arrival of this front in the Tulsa area. Both the synoptic-scale trajectories (Figure 4.2) and the local (mesoscale) trajectories (Figure 4.3) indicate southerly winds in the Tulsa area. The forward trajectories of the urban air parcel (Figure 4.4a) show the northward transport of the urban air until midafternoon when the effect of the front produced stagnation in Tulsa.

The steady southerly winds in Tulsa, before the arrival of the front, resulted in an identifiable ozone plume north of Tulsa. The evolution of the urban ozone plume is most easily visualized by the concentration/distance plots shown in Figure 4.9. The elevated ozone concentrations north of Tulsa were first apparent at Sperry at 0900. The ozone concentration increased more rapidly at Vera, however, as shown in the hour 1100 plot, and the daily maximum ozone concentration in the network of 0.135 ppm was measured at Vera at hour 1300.

Even though southerly winds were still measured during hour 1500 in the network, significant reductions in the ozone concentrations were observed north of Tulsa during hour 1500. Cloudiness produced by the approaching front significantly reduced the solar radiation during hour 1400, and temperatures also decreased rapidly after 1400. Both of these factors may have had an impact on the reduced ozone concentrations.

Using the procedure outlined in the introduction, the net impact of Tulsa emissions on ozone formation can be estimated by subtracting the background ozone concentration from the maximum ozone concentration measured downwind of Tulsa. On July 21, the maximum ozone concentration in the network of 0.135 ppm was measured at Vera at 1300. The average of the 1000 and 1100 ozone concentrations at Liberty Mounds was 0.045 ppm. The difference, 0.090 ppm, is an estimate of the net ozone production as a result of activities in and around Tulsa.

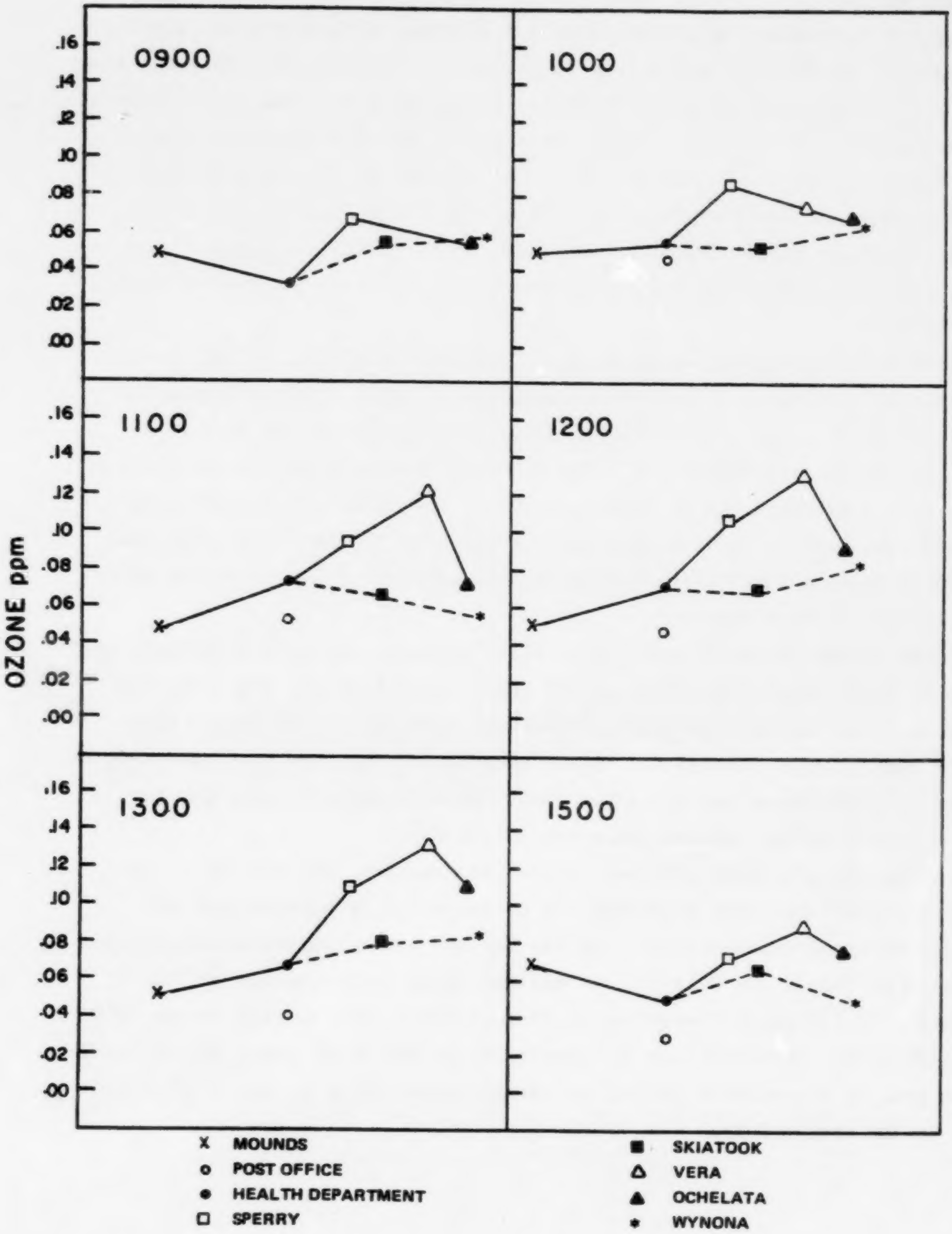


Figure 4.9. Ozone concentration/distance plots for July 21, 1977.

### 4.2.4 Analysis of July 22 and 23, 1977

The meteorological conditions in Tulsa on July 22 and 23 were quite different than those on July 21. A stationary front was in the vicinity of Tulsa by 0700 EST on July 22, and its position had not changed significantly by 0700 EST on July 23 (Figure 4.1d). This front produced variable winds in Tulsa on July 22 and 23. The synoptic scale trajectories for both July 22 and 23 indicate that there was only weak transport in the Tulsa area for at least the last 12 hours prior to both air parcel arrival times (Figure 4.2). The maximum temperatures were 35° C (95° F) and 37° C (99° F) on July 22 and 23, respectively (Figure 4.5). There was excellent solar radiation on both days (Figure 4.6). The forward trajectories of the urban air parcel show that there was almost no air parcel advection on July 22, and only slow northward transport on July 23. In general, on July 22 and 23, Tulsa experienced similar meteorological influences. The lack of any significant transport and plentiful sunshine resulted in the occurrence of the network maximum ozone concentrations at both city sites on July 22. Although the maximum ozone concentrations measured at both city stations on July 23 were higher than average for July, slow northward transport was occurring and the network maximum of 0.118 ppm occurred at Vera.

There were low concentrations of NMHC and oxides of nitrogen at the Post Office site during hours 0600 to 0900 CDT on July 22 (Table 4.2). The concentration of acetylene, however, was equal to the mean for July, and the concentration of n-butane was less than half of the mean for July, perhaps indicating that the refinery area, located southwest of the site did not contribute to the NMHC concentration at the Post Office as much as it had on July 21 when southerly winds were measured in Tulsa. On the morning of July 22, Liberty Mounds measured very high concentrations of NMHC and oxides of nitrogen from hours 0600 to 0900 CDT, indicating, perhaps, that southerly movement of Tulsa air had taken place.

The ozone profiles for July 22 from Sperry, Skiatook, Vera, and Ochelata (Figure 4.8) were all substantially different in appearance from those of July 21. The maximum ozone concentrations measured at Sperry, Skiatook, Vera, and Ochelata on July 22 were reduced from the maximum ozone concentrations measured on July 21 by 0.026, 0.022, 0.031, and 0.029 ppm, respectively. The maximum ozone concentrations measured at the Post Office and Health Department of 0.127 and 0.124 ppm were elevated over the maximum ozone concentrations measured on July 21 by 0.077 and 0.059 ppm, respectively. Liberty Mounds measured a maximum ozone concentration of 0.081 ppm, an increase of only 0.013 ppm over the maximum for the previous day.

The forward trajectory of the urban air parcel (Figure 4.4b) shows the stagnation of air in the Tulsa area during the afternoon of July 22. During the early morning hours there was transport to the south and the Liberty Mounds site. The ozone distribution in the network on July 22 was nearly constant until 1100 (Figure 4.10) when the urban stations first measured ozone concentrations in excess of those measured at the other stations. The ozone concentrations continued to rise at the urban stations until the maxima were reached at hour 1300.

On July 23, the maximum ozone concentrations measured at both the Post Office and Health Department sites (0.100 and 0.104 ppm) were considerably higher than the mean maximum ozone concentrations during July of 0.067 ppm for the Post Office and 0.074 ppm for the Health Department. Concentrations of NMHC and oxides of nitrogen during the 0600 to 0900 CDT sampling period at the Post Office were not unusually high. At the Health Department there was a higher than average NMHC sum but the difference was mostly caused by an increase in the high sum of alkanes. Vehicular emissions were probably lower in the 0600 to 0900 CDT sampling period because July 23 was a Saturday; however, low-speed, variable winds produced conditions that inhibited the dispersion of morning emissions in the urban area.

Between 0600 and 1000 CST the ozone concentrations increased rapidly at each station in the network. These increases were probably a result of ozone mixing to the surface from above the radiation inversion. The forward trajectories of the urban air parcel show that there was northward transport during the morning hours to Vera, and that stagnation began in the early afternoon. This is important because the maximum ozone concentration of the day of 0.118 ppm occurred at Vera at 1200. It is likely that the high ozone concentrations measured at Vera were a result of ozone synthesis in an air parcel that was transported from the urban area to Vera during the morning hours and that then stagnated in the area of Vera. The high ozone concentra-

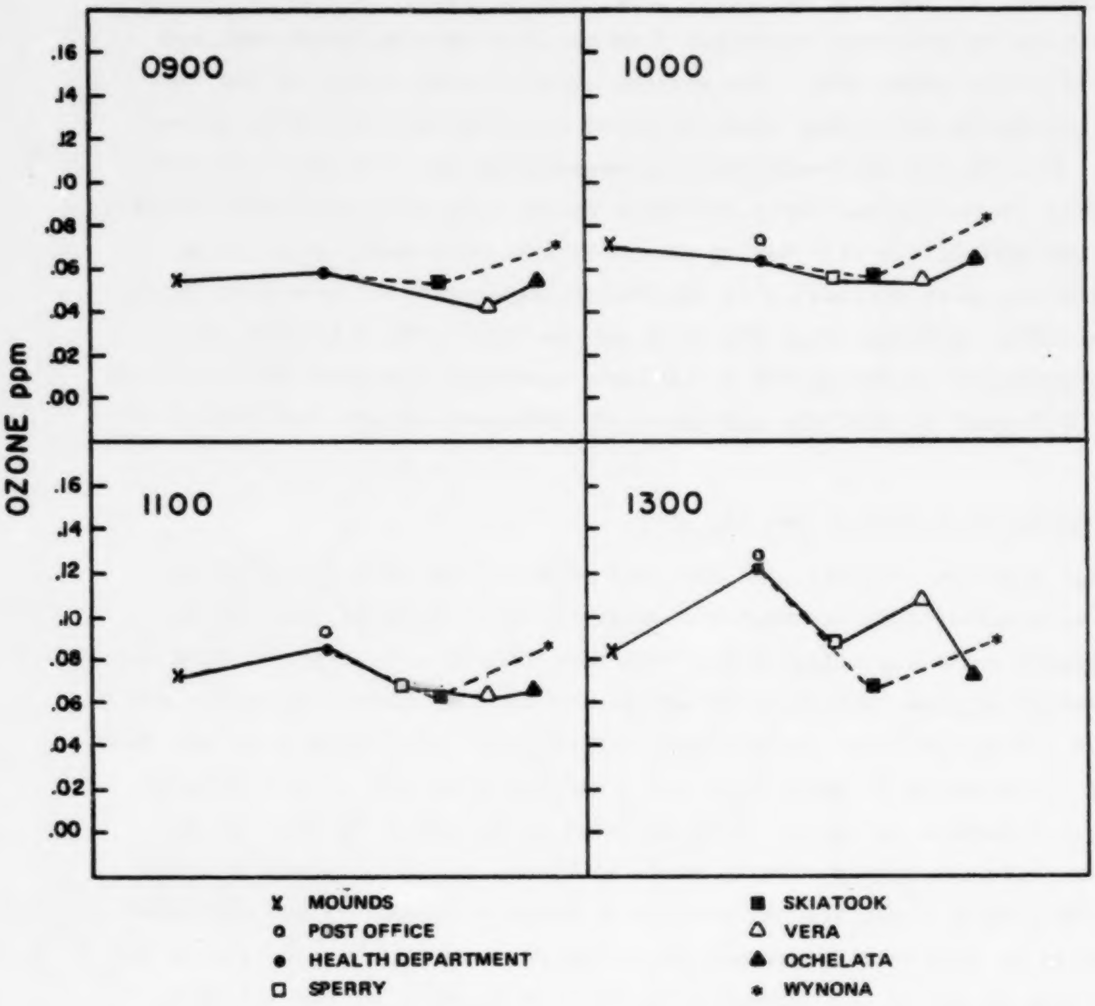


Figure 4.10. Ozone concentration/distance plots for July 22, 1977.

tions measured at the city stations, then, were probably the result of ozone synthesis due to precursor emissions from the late morning hours that had stagnated in the urban area. The maximum ozone concentrations at the Post Office and Health Department sites occurred at hours 1500 and 1200, respectively. Both NO and $NO_2$ concentrations measured at the city stations were relatively low during the early afternoon hours. The continued ozone synthesis at the Post Office site during the early afternoon hours while ozone concentrations were decreasing at the Health Department may have been due to continued NMHC emissions from that area of the city. The data from the Beckman-automated chromatograph do indicate continued elevated concentrations (0.3 to 0.7 ppmC) of NMHC through the early afternoon at the Post Office site.

### 4.2.5 Analysis of July 24 and 25, 1977

High pressure centered over the Gulf of Mexico on July 24 and 25 resulted in southwesterly and westerly winds in Tulsa (Figures 4.7e and f). The synoptic-scale trajectories for both days (Figure 4.2) indicate that air was transported from central Texas and passed near Oklahoma City on its way to Tulsa. Both the local (mesoscale) back trajectories (Figure 4.3) and the forward trajectories (Figures 4.4d and e) of the urban air parcel indicate northeast transport in the vicinity of Tulsa on July 24. On July 25 the local trajectories show northerly winds at Wynona and Vera, westerly winds at the Post Office, and southerly winds at Liberty Mounds. These inconsistent winds at 1800 were the result of a wind shift that occurred late in the day on July 25 due to the passage of a front as it moved across the Tulsa area. The forward trajectories of the urban air parcel show easterly transport on July 25. Skies were clear on both days and temperatures reached 40° C (104° F) and 41° C (106° F) on July 24 and 25, respectively (Figures 4.5 and 4.6).

At the Post Office, high concentrations of nonmethane hydrocarbons were measured during the 0600 to 0900 CDT sampling period on both July 24 and 25 (Table 4.2). On July 24, a very low concentration of acetylene of 2.8 ppbC and a high concentration of alkanes were measured. July 24 was a Sunday and the low traffic volume accounted for the low acetylene concentration. The NO concentration measured at the Post Office of 0.086 ppm from 0600 to 0900

CDT was much higher than the average value for July. The low acetylene concentration during the same time period indicated that the air parcel at the Post Office from 6-9 a.m. CDT probably did not contain substantial amounts of automobile emissions. It is assumed, therefore, that the refinery area was the major contributor to the 0600 to 0900 CDT precursor concentrations measured at the Post Office. On July 25, the high concentration of nonmethane hydrocarbons measured at the Post Office site was again due to high concentrations of alkanes. The average NO concentration during the 0600 to 0900 CDT period had decreased considerably on July 25 from that measured on July 24. At the Health Department, the concentrations of nonmethane hydrocarbons and oxides of nitrogen on July 24 and 25 were not unusually high compared to the average values for July.

All three trajectory analyses for both July 24 and 25 show that the urban air was transported to the east of the network monitoring stations. On July 24 at the Liberty Mounds, Post Office, Health Department, Sperry, Skiatook, and Ochelata sites, the ozone concentrations were representative of conditions expected in areas that were not strongly influenced by urban sources.

At both Wynona and Vera, however, maximum ozone concentrations of 0.104 and 0.105 ppm were measured. These maximum concentrations, which occurred at hour 1100 at Wynona and 1300 at Vera, were at least 20 ppb greater than the concentrations measured at other stations in the network at the same time. Also, the local trajectory for air arriving at Vera at 1300 passed directly over Skiatook not more than 2 hours before 1300. In addition, the ozone concentrations at both Wynona and Vera did not reach the daily maximum concentration suddenly, but increased to their maximum concentrations slowly, in a manner typical of ozone synthesis.

If the ozone measured at Wynona and Vera were produced by Tulsa emissions alone, some recognizable influence should have been seen at Sperry, and if emissions from Oklahoma City were responsible, it seems that Skiatook would have measured elevated ozone concentrations also. Thus the cause of the elevated ozone concentrations measured at Wynona and Vera on July 24 is not clear from the data that are available.

On July 25 the maximum ozone concentrations measured at many of the network stations occurred at or after 1700. Even at Liberty Mounds and Vera, where the daily maximum concentrations were measured earlier in the day, increasing ozone concentrations were observed during the evening hours. During the afternoon of July 25, the same situation just described for July 24 was observed again. Vera and Wynona measured ozone concentrations that were considerably higher than at any other station. Westerly winds and eastward transport were again indicated by the wind data throughout the network. Again, the cause of the high ozone concentrations measured at Wynona and Vera relative to the other network stations is not clear.

The maximum ozone concentration in the network was 0.123 ppm at 1800 at Wynona. The local trajectories at 1800 showed the wind shift that was presumably caused by a frontal passage at this site. The front moved through Tulsa from north to south and the peak ozone concentrations occurred progressively later from the northern to the southern sites. The ozone increases late in the day on July 25 appear to be related to the frontal passage. The ozone was either brought to the surface from aloft by a disturbance created by the front, or there were high ozone concentrations in the air mass behind the front. Since measurements of ozone were not made north of the front's position or aloft, as part of this study, it was not possible to determine the source of the ozone measured in Tulsa late in the day. It is unlikely, however, that Tulsa emissions were the direct cause of that ozone.

## 4.3 JULY 28 THROUGH 30, 1977: CASE STUDY

### 4.3.1 Introduction

The days July 28 through 30 (Thursday through Saturday) were chosen for case study analysis primarily because the maximum ozone concentration of the summer study period at Liberty Mounds, 0.127 ppm, occurred at 1700 on July 29. This was unusual since this site most often reported rural, background ozone concentrations.

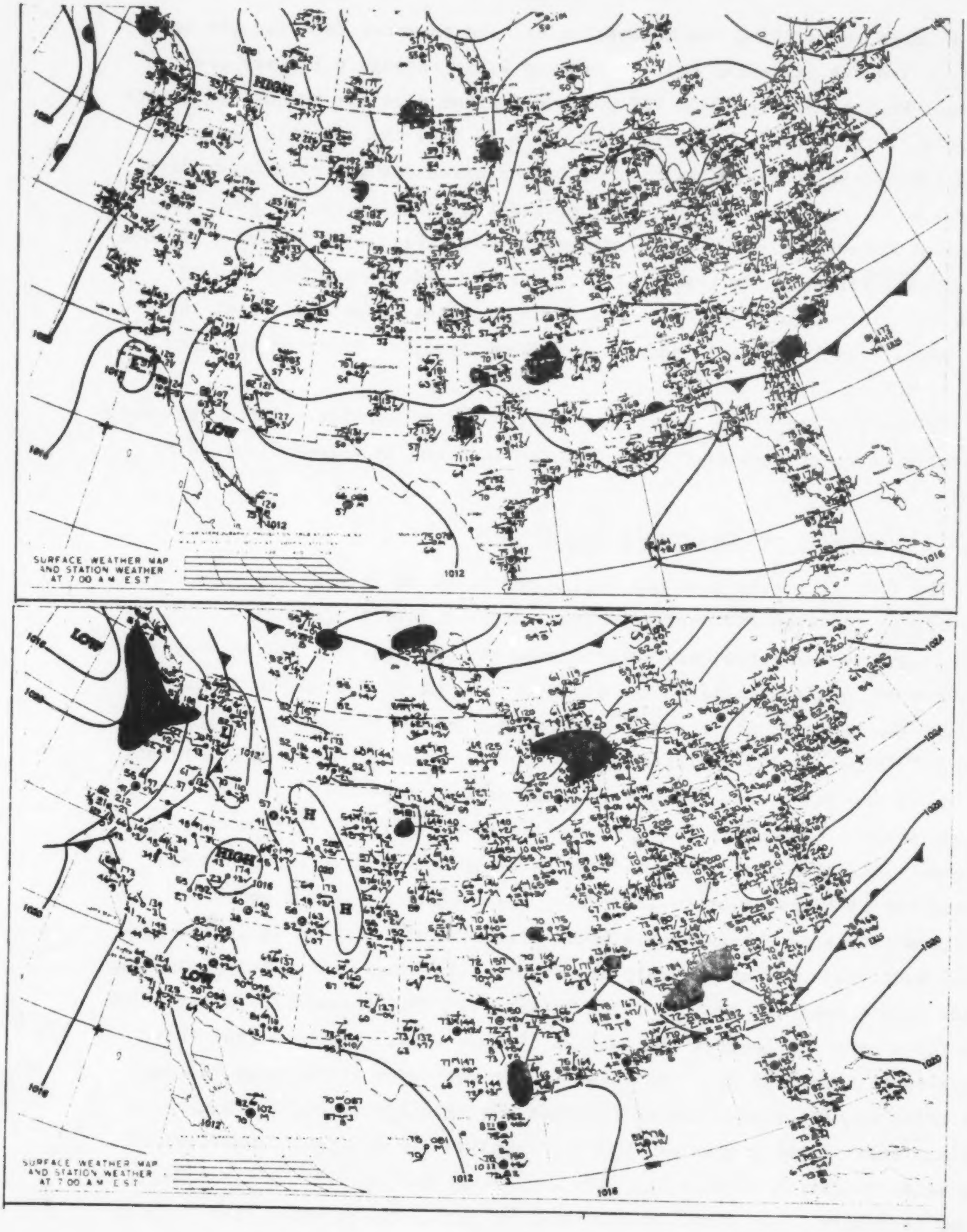
A frontal system was the dominant meteorological influence on Tulsa on both July 28 and 29. On July 30 there were clear skies and steady southerly winds, the most common meteorological conditions observed in Tulsa, and this day was included in the analysis to show the contrast between it and July 29.

Figures summarizing the meteorological and chemical data for the case study period are presented below. Figures 4.11a through 4.11e are the National Weather Service 0700 EST surface weather maps for the United States for July 27 through 31. Figures 4.12 and 4.13 show the synoptic scale and local (mesoscale) backward air parcel trajectories for the case study days. Figures 4.14a through 4.14c are the forward trajectories of the urban air parcel at selected times of each case study day. Figures 4.15 and 4.16 show the diurnal variation in temperature, and solar radiation. Figure 4.17 shows the diurnal profiles of hourly average values of NO and $NO_2$ at the two city sites, and Figure 4.18 shows the diurnal profiles of ozone for each site in the network.

Values for individual hours of data for the meteorological and chemical parameters are not presented here, but can be found in Volume II of this report.

### 4.3.2 Overview of the Case Study Period

The frontal system that had influenced Tulsa on July 25 was shown south of Tulsa on the 0700 EST surface weather map for July 28 (Figure 4.11b). A large high-pressure area was centered over the northeastern States, but the presence of the front limited the influence of the high pressure area on Tulsa. The synoptic-scale trajectory for air parcel arrival in Tulsa at 0600 CST (Figure 4.12) indicates that there was very little large-scale air motion in the Tulsa area for the 48 hours preceding 0600 on July 28. The synoptic-scale trajectory for air parcel arrival in Tulsa at 1600 CST, however, indicates that there had been slow transport from the southwest during the 24 hours prior to 1600 CST. The trajectory passed near the Oklahoma City area during the 24 hours preceding its arrival in Tulsa. The local back trajectories for July 28 (Figure 4.13) show that mostly southerly winds were present in the immediate Tulsa area. The forward trajectories of the Tulsa urban air parcel for July 28 (Figure 4.14a) indicate that there was slow transport of air from Tulsa to the northwest all through the day. The solar radiation measured at Skiatook was relatively low, reaching a maximum only slightly greater than 1.0 langleys per minute. Comparison of the solar radiation profile for July 28 to that for July 30, a clear day, shown in Figure 4.16, displays the relative depletion of solar radiation on


HIGH
LOW
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. EST
1012
1016
LOW
HIGH
LOW
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. EST
1012
1016
1020
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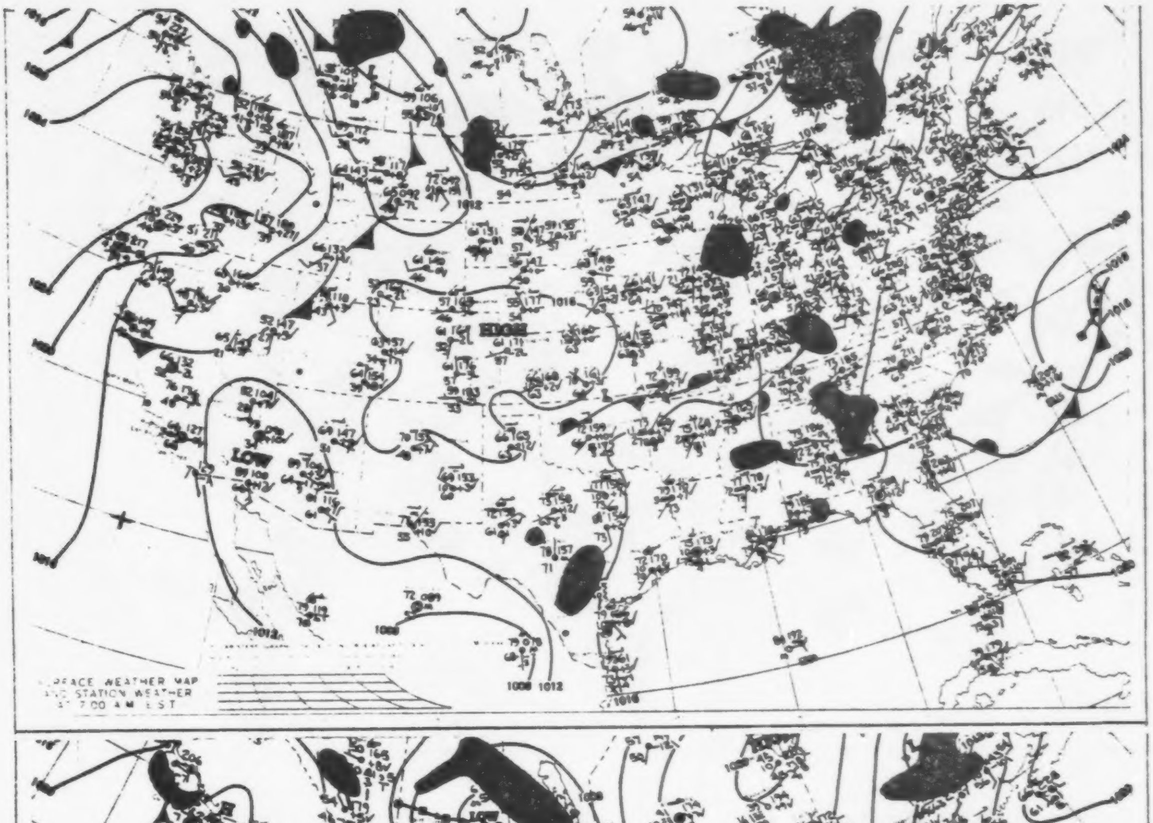
Figures 4.11a and 4.11b. United States surface weather maps for July 27 and July 28, 1977.


SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.
HIGH
LOW
1012
1008
1016
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.
LOW
1012
1016

Figures 4.11c and 4.11d. United States surface weather maps for July 29 and July 30, 1977.

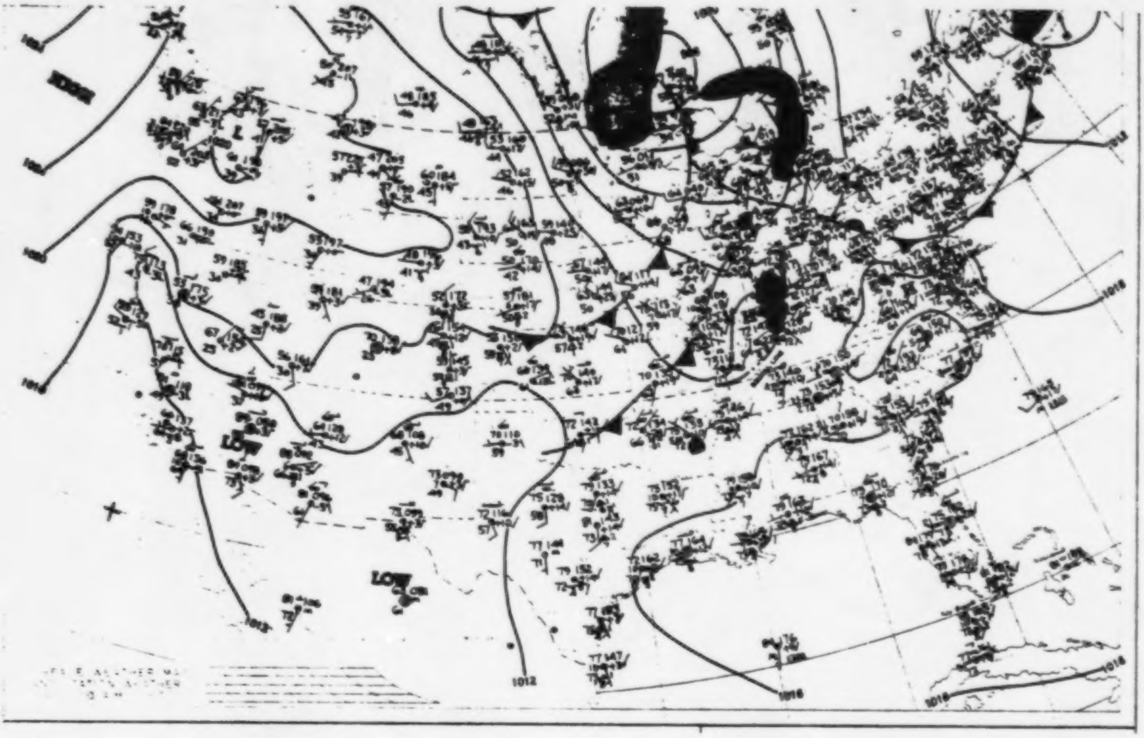


Figure 4.11e. United States surface weather map for July 31, 1977.

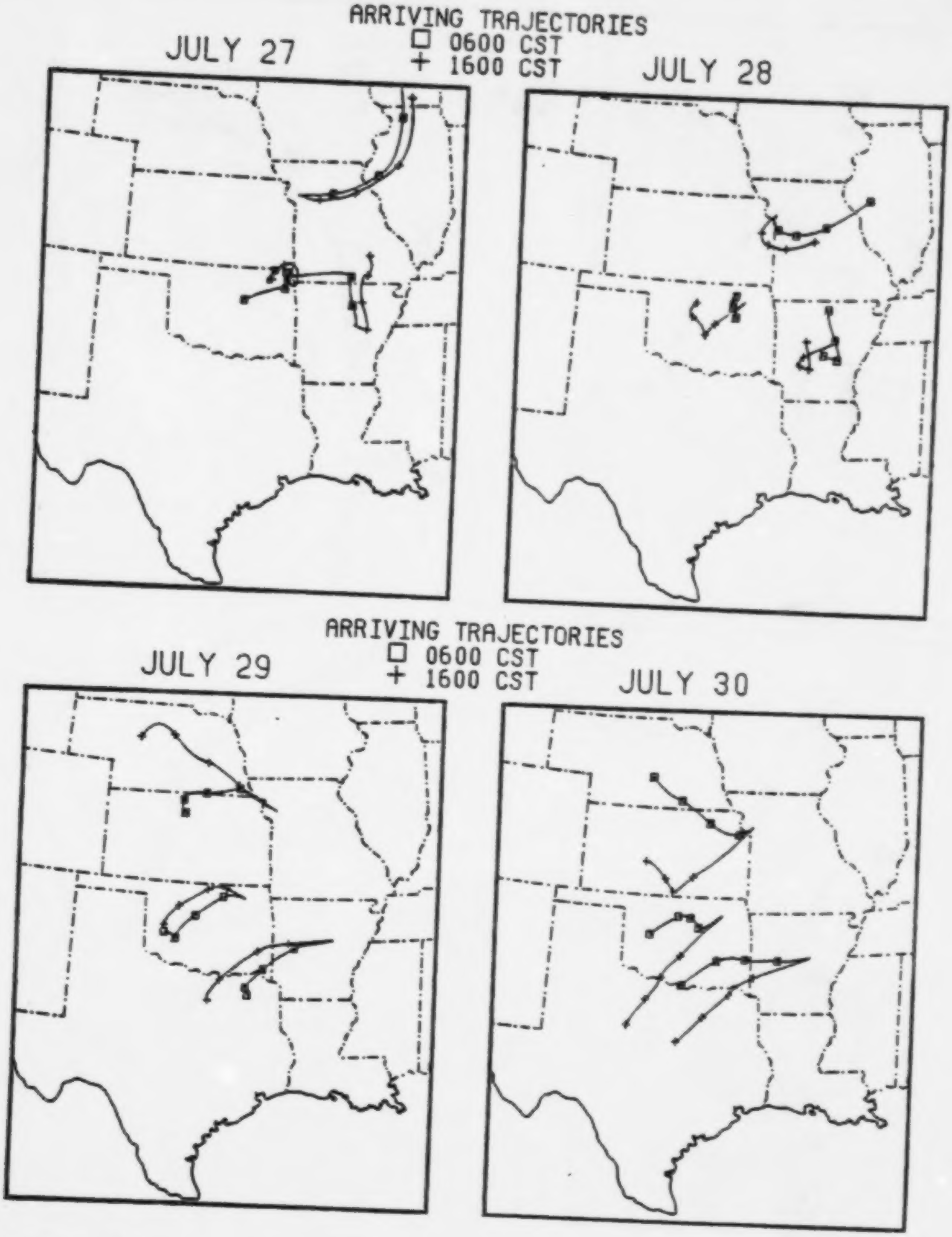
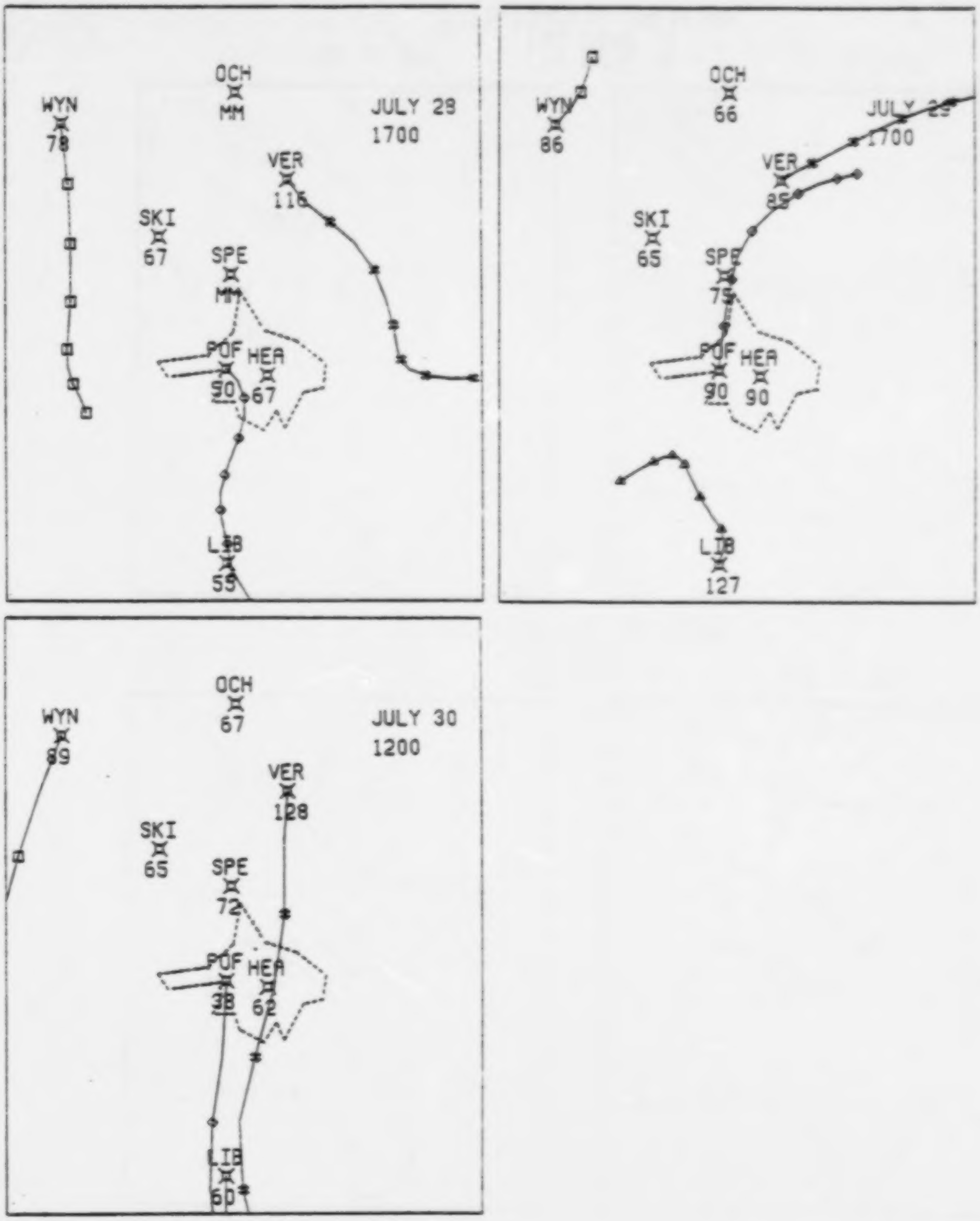

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
JULY 27
JULY 28
ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
JULY 29
JULY 30

Figure 4.12. Synoptic scale trajectories for case study period July 28-30, 1977.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JULY 29
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SKI
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SPE
75
POF
90
HEA
90
LIB
127
OCH
67
WYN
89
JULY 30
1200
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38
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62
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60

Figure 4.13. Mesoscale trajectories for case study period July 28-30, 1977.

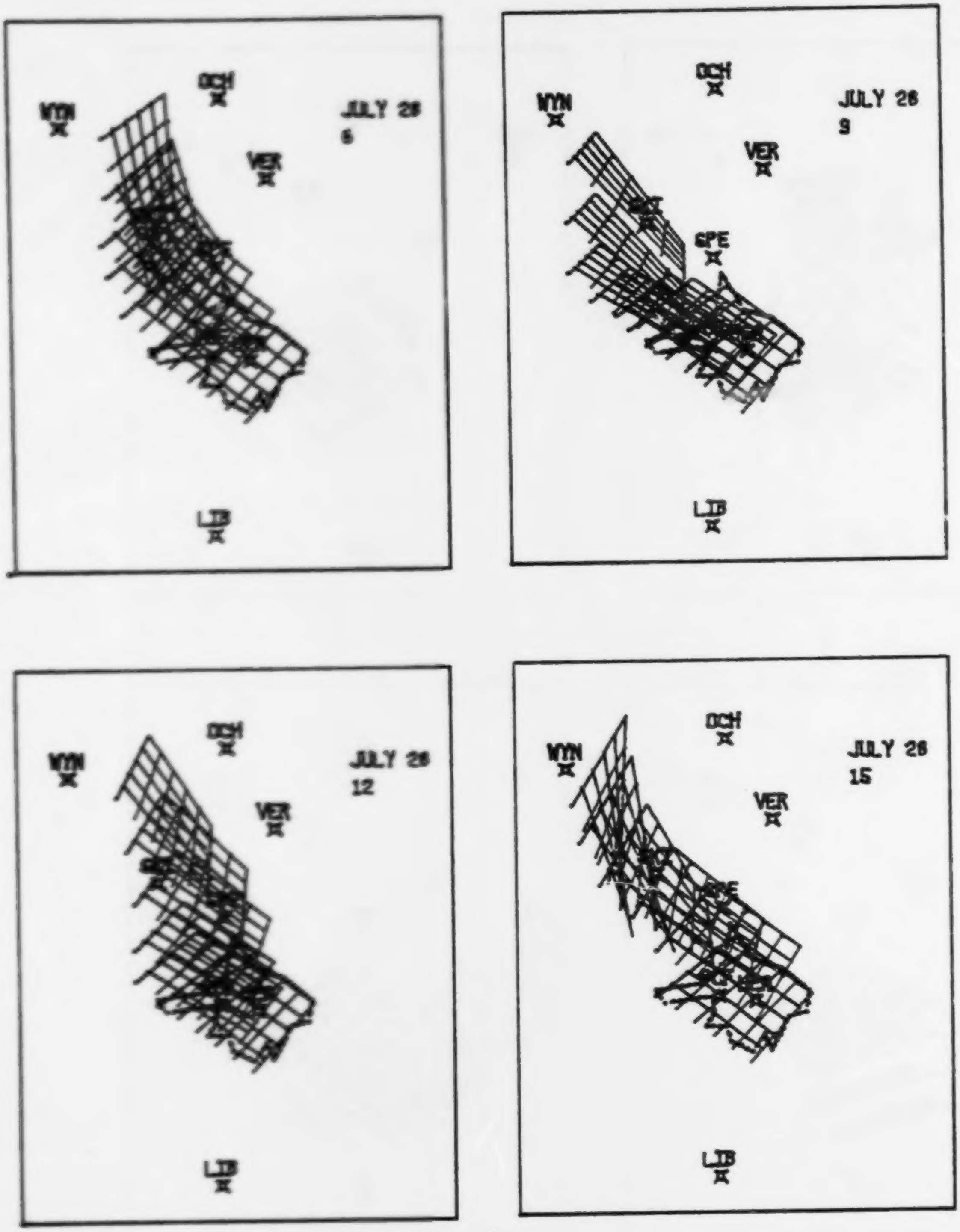

Figure 4.14a. Forward air parcel trajectories for July 28, 1977.

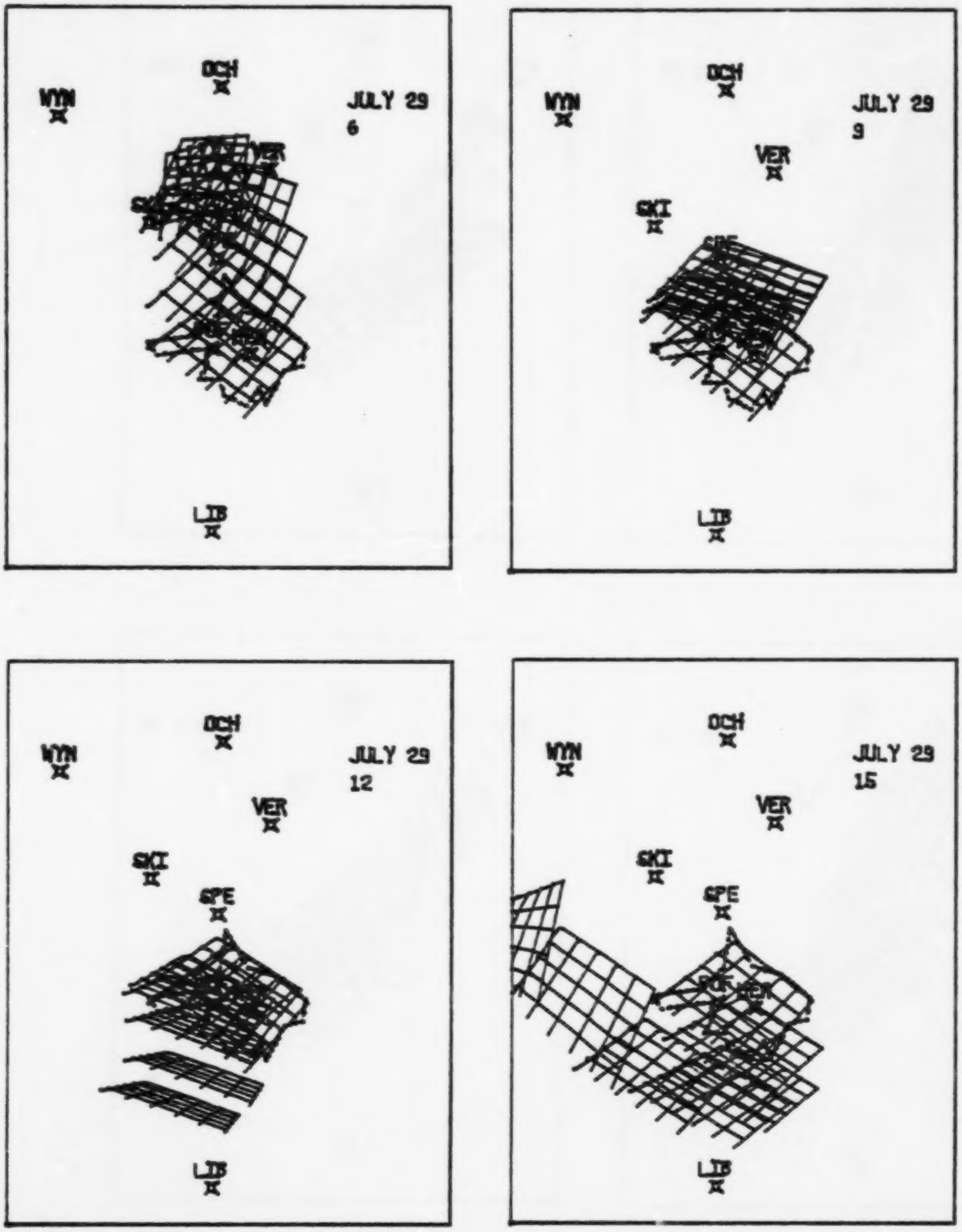

Figure 4.14b. Forward air parcel trajectories for July 29, 1977.

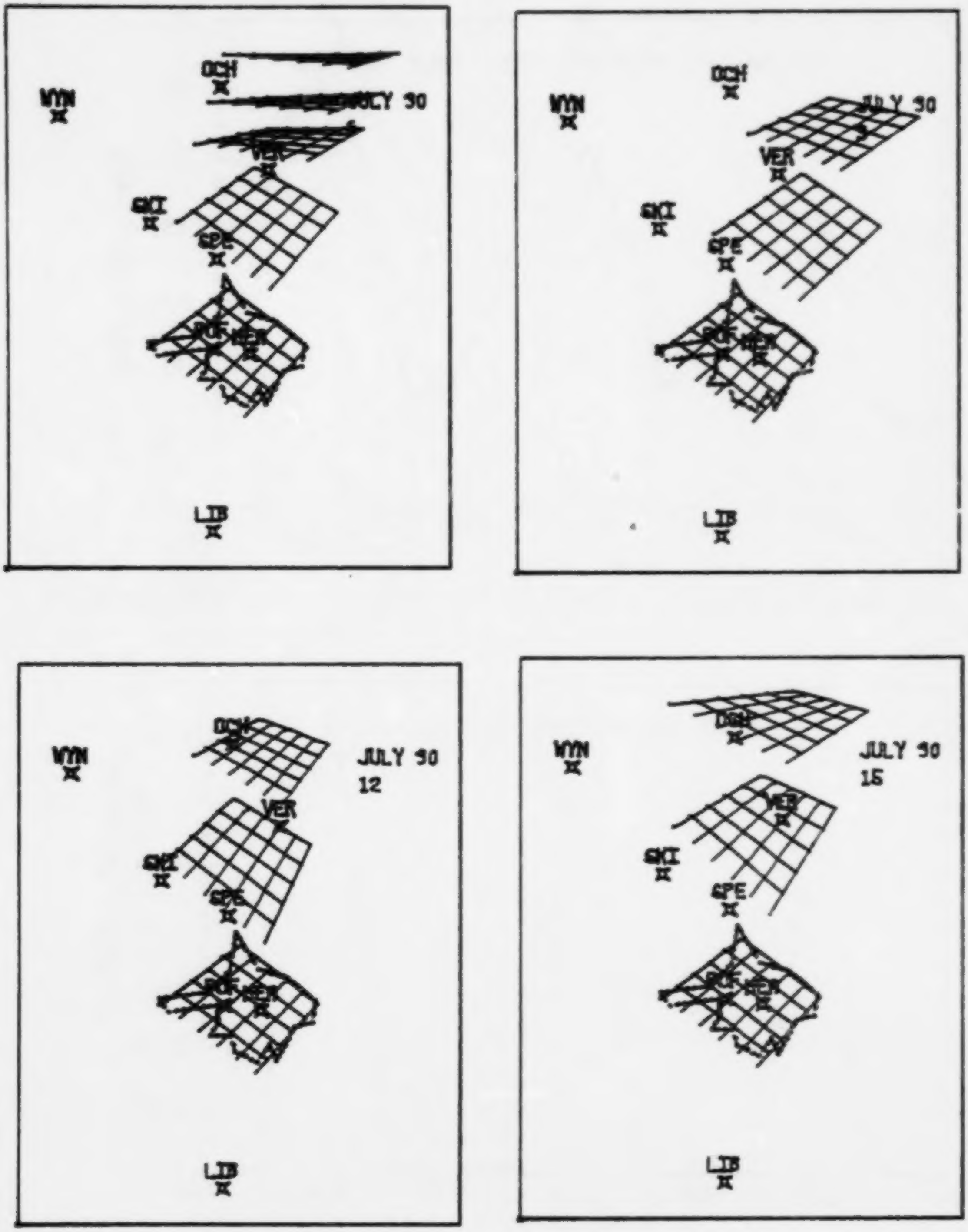
OCH
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Figure 4.14c. Forward air parcel trajectories for July 30, 1977.

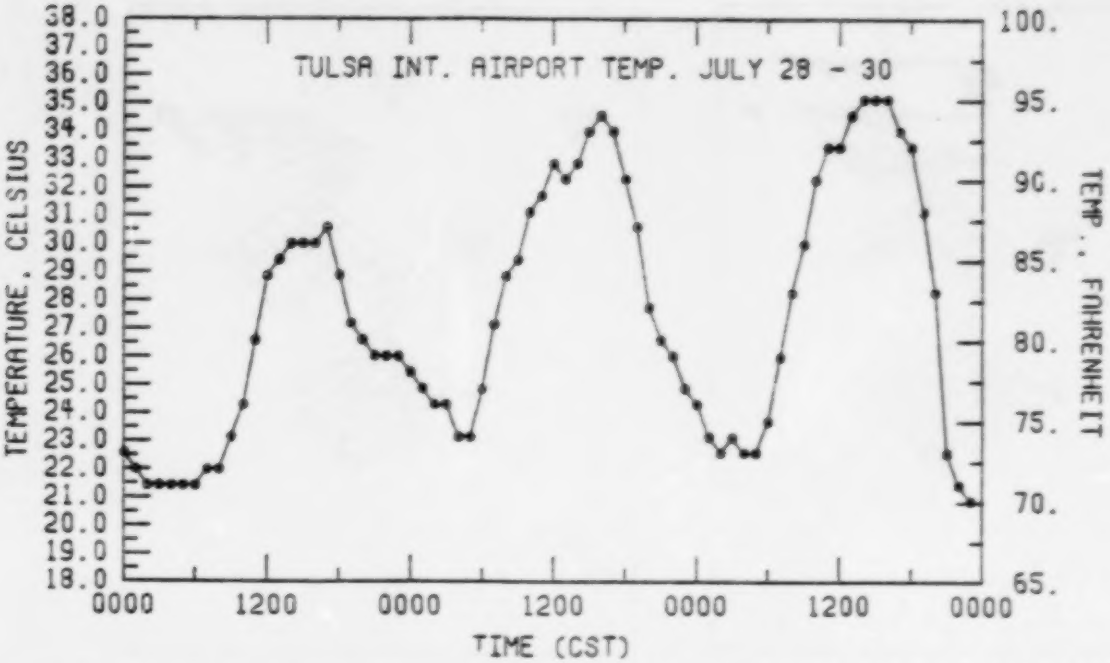


Figure 4.15. Diurnal variation of temperature for the period July 28-30, 1977.

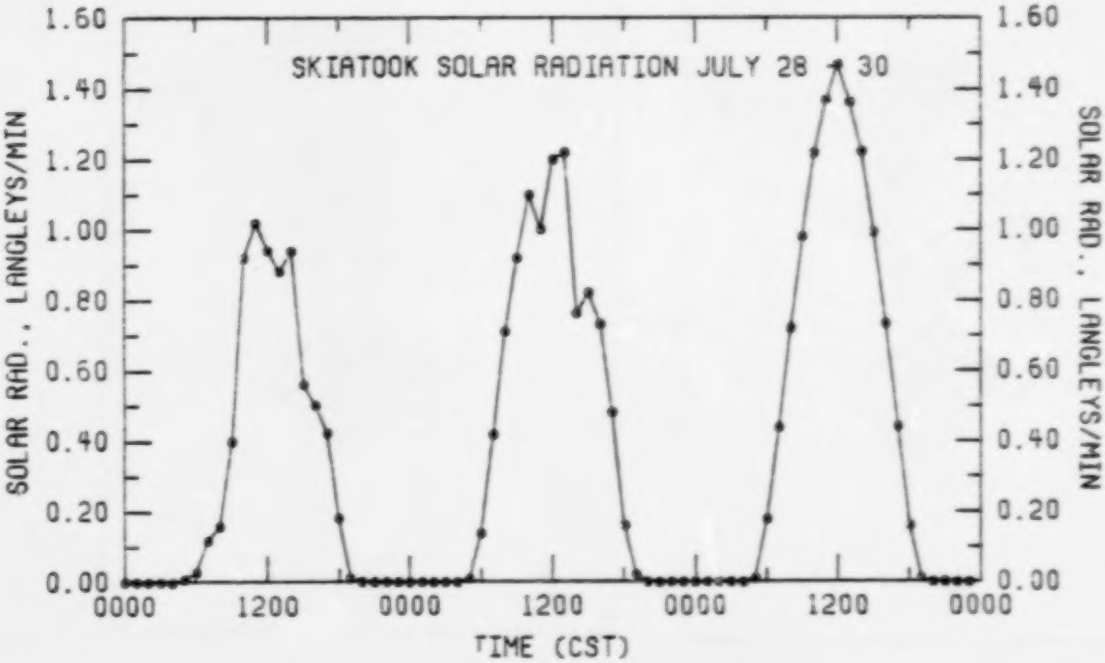


Figure 4.16. Diurnal variation of solar radiation for the period July 28-30, 1977.

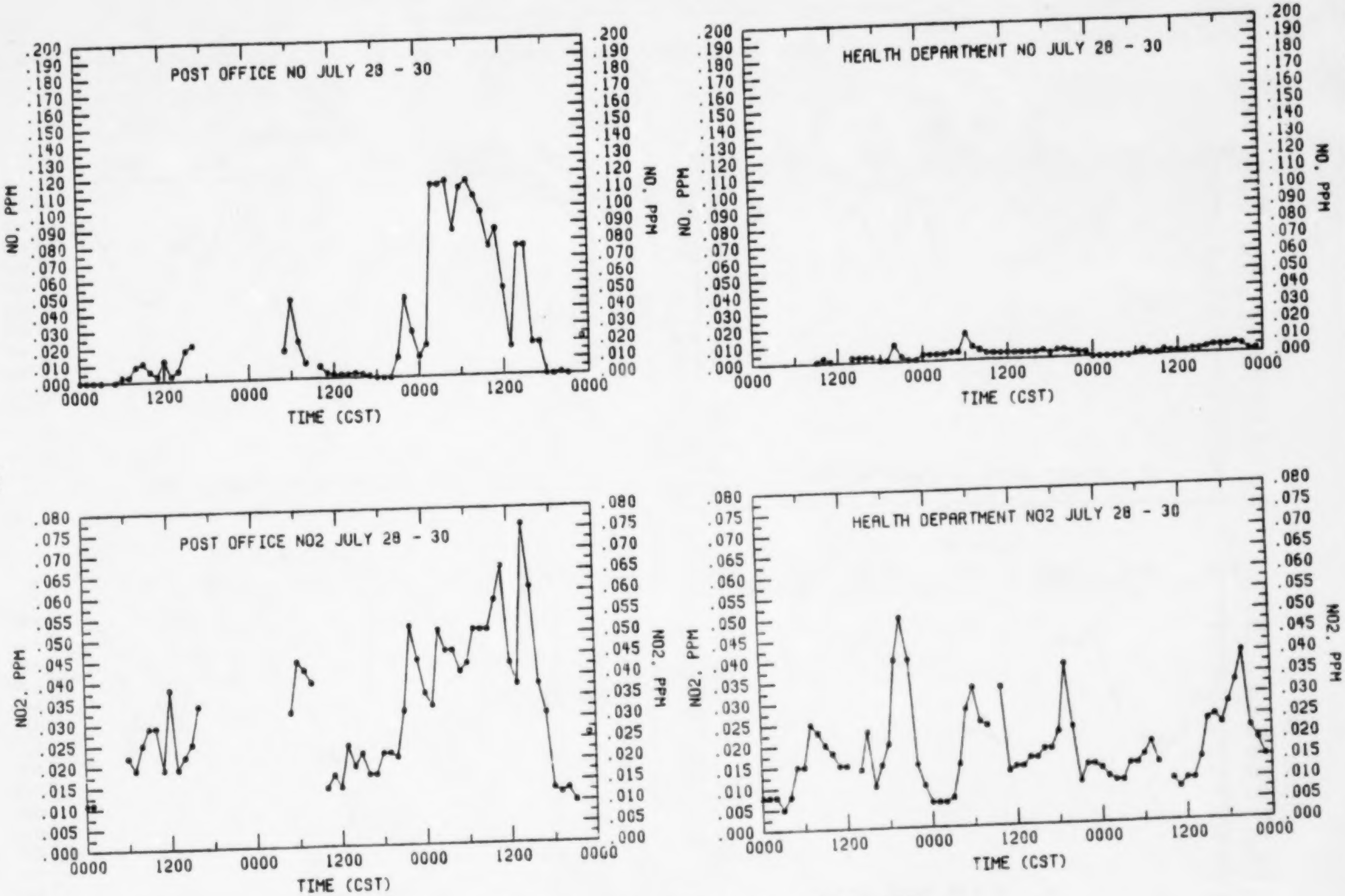


Figure 4.17. Diurnal variations of NO and $NO_2$ for the period July 28-30, 1977.

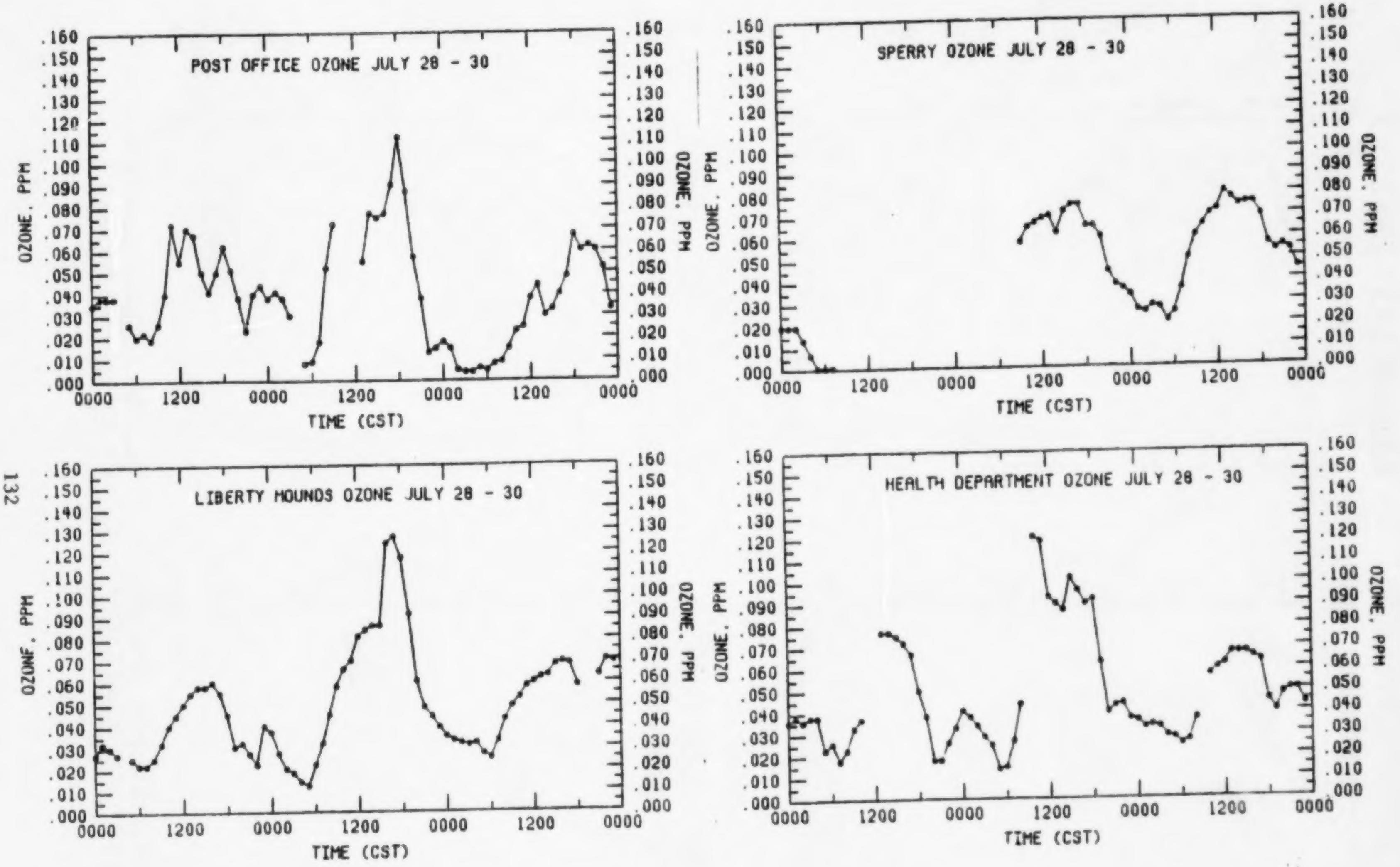


Figure 4.18. Diurnal variation of ozone for the period July 28-30, 1977.

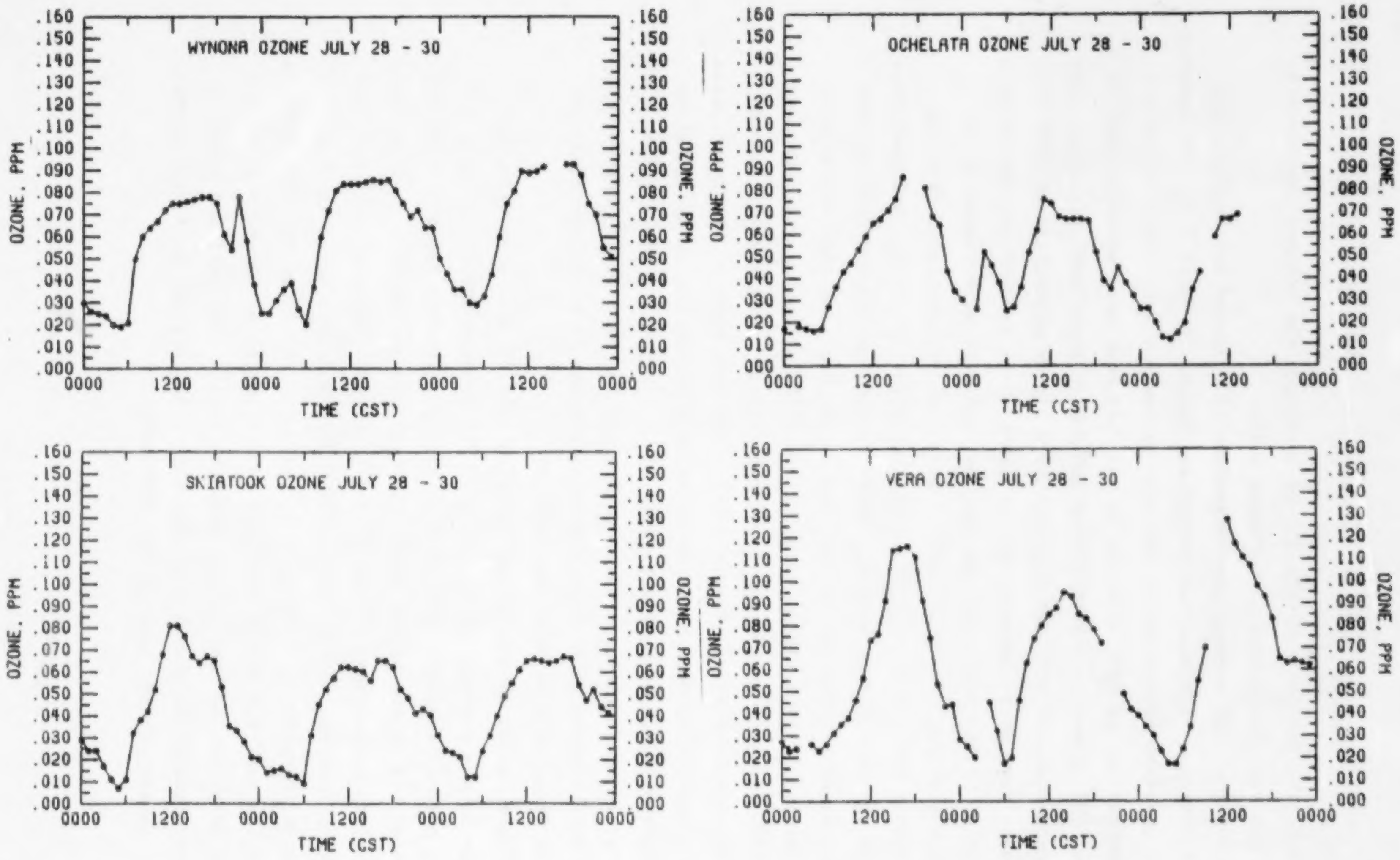


Figure 4.18. Diurnal variation of ozone for the period July 28-30, 1977. (continued).

July 28. Due to the low availability of sunshine, the maximum temperature in Tulsa was also relatively low (Figure 4.15).

The 6-9 a.m. CDT average concentrations of selected hydrocarbon species, oxides of nitrogen, and selected ratios are listed in Table 4.3. The monthly means and standard deviations of the same parameters are listed in Table 4.1. Low concentrations of NMHC relative to the July mean were measured between 6 and 9 a.m. CDT at both the Post Office and Health Department stations. The low concentrations of NMHC and substantially higher percentage of NMHC due to vehicular emissions implies that the urban stations were influenced to a lesser extent by the refinery area than on days with more southerly or southwesterly winds. The NMHC concentration was not available from the Liberty Mounds station on July 28. The concentration of $NO_x$, averaged from 6-9 CDT at the Post Office station, of 0.104 ppm was considerably greater than the July mean. Most of the $NO_x$ was as NO, implying that a nearby source, possibly city traffic, contributed to that high $NO_x$ concentration.

By 0700 EST on July 29, the front had drifted north and was located just to the north of Tulsa (Figure 4.11). The influence of the front again produced scattered cloudiness in Tulsa on July 29 and the solar radiation was considerably less than that of July 30, a clear day (Figure 4.16). The synoptic-scale trajectories indicated that air had been slowly transported from the southwestern part of Oklahoma, during the 48 hours preceding its arrival in Tulsa at both 0600 and 1600 CST.

The local winds in and around Tulsa on July 29 were significantly influenced by the presence of the front. The forward trajectories of the urban air parcel (Figure 4.14) indicate that air leaving Tulsa at 0600 CST travelled slowly to the north, while the trajectories for air leaving Tulsa at 0900 indicate that very little motion occurred. Both the 1200 and 1500 trajectories indicate southerly transport followed by a shift in winds that moved air to the west of Tulsa late in the day. The local back trajectories (Figure 4.13) indicate air arriving in Vera from the northeast and curving around to arive at the Post Office from the north. The last few hours of the Liberty Mounds trajectory indicate that urban air may have been transported to Liberty Mounds late in the afternoon.

TABLE 4.3 0500 TO 0800 CST AVERAGE CONCENTRATIONS OF SELECTED HYDROCARBONS AND OXIDES OF NITROGEN, AND DISTRIBUTIONS FOR JULY 28, 29, AND 30, 1977

| | Σ NMHC | Beckman | Σ Alkenes | Acetylene | n-Butane | % Tailpipe emissions | NO | $NO_2$ | $NO_x$ | $\frac{\Sigma\ NMHC}{NO_x}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Post Office | | | | | | | | | | |
| July 28 | 361.7 | 0.36 | 50.7 | 13.6 | 24.8 | 58 | 0.083 | 0.021 | 0.124 | 2.92 |
| July 29 | 566.6 | 0.54 | 59.1 | 17.8 | 62.4 | 49 | 0.014 | 0.039 | 0.054 | 10.49 |
| July 30 | 771.1 | 0.54 | 90.3 | 6.0 | 149.6 | 12 | 0.012 | 0.045 | 0.057 | 13.53 |
| Health Department | | | | | | | | | | |
| July 28 | 173.0 | 0.16 | 37.6 | 9.4 | 13.2 | 84 | - | 0.018 | - | - |
| July 29 | 396.7 | 0.34 | 31.4 | 13.4 | 43.2 | 52 | 0.010 | 0.029 | 0.038 | 10.44 |
| July 30 | 179.3 | 0.00 | 13.5 | 2.6 | 10.0 | 22 | 0.001 | 0.016 | 0.018 | 9.96 |
| Liberty Mounds | | | | | | | | | | |
| July 28 | - | - | - | - | - | - | 0.001 | 0.004 | 0.005 | - |
| July 29 | - | - | - | - | - | - | 0.005 | 0.010 | 0.015 | - |
| July 30 | 162.4 | - | 8.4 | 2.0 | 8.0 | 19 | 0.005 | 0.005 | 0.009 | 18.04 |

The 6-9 a.m. CDT NMHC concentrations measured at the Post Office and Health Department stations were considerably greater than the July mean. The percentage of NMHC due to vehicular emissions, however, was not significantly different than the July mean at either of the stations. In addition, the 6-9 CDT average $NO_x$ concentration at the Post Office was lower than average, while at the Health Department the concentration of $NO_x$ on July 29 was nearly double the July mean. Therefore, a complex interaction between local source areas and local winds was active in Tulsa on July 29. The highest hourly average ozone concentration of the summer at Liberty Mounds of 0.127 ppm was measured at 1700 on July 29. The ozone measured at Liberty Mounds probably resulted from the high ozone precursor concentrations measured in the city, which were producing ozone while being slowly transported to the south.

By July 30 the front was well out of the Tulsa area (Figure 4.11). An area of high pressure was centered off the Florida coast. Steady southerly winds and clear skies were observed in Tulsa all day. The synoptic trajectories (Figure 4.12) for July 30 show air arriving at 0600 from the southwest after it had passed north of Oklahoma City. The air arriving at 1600 came from central Texas 48 hours earlier and passed near Oklahoma City. The local back trajectories (Figure 4.13) show steady southerly winds, which caused the trajectories to pass right over Tulsa and move on to the stations north of Tulsa. The forward trajectories of the urban air parcel (Figure 4.14) also indicate steady northward transport of air from Tulsa.

Both the NMHC and $NO_x$ measured during the 6-9 CDT period on July 30 at the Post Office of 771.1 ppbC and 0.150 ppm, respectively, were considerably higher than the July means. At the Health Department, however, both the NMHC and $NO_x$ concentrations were lower than the July means. Liberty Mounds also measured low concentrations of precursors during the 6-9 a.m. CDT measurement period. Only 12 percent of the very high concentration of NMHC measured at the Post Office station was contributed by vehicular emissions, which was considerably less than the average for July of 40 percent. The southerly winds seem to carry the industrial-type emissions from the refinery area to the Post Office station without influencing the Health Department sample.

### 4.3.3 Analysis of July 28, 1977

The dominant meteorological influence on Tulsa on July 28 was a large high-pressure area centered over the northeastern states. The influence of the high pressure on Tulsa, however, was modified by the presence of a stationary front located just south of the Oklahoma and Texas border (Figure 4.11b). There were overcast skies in Tulsa on July 28 until the 1000 hour, and scattered cloud cover for the remainder of the day. One result of the cloud cover was that temperatures were lower than average. The synoptic-scale trajectories (Figure 4.12) indicate that the air parcel arriving in Tulsa at 0600 had moved very little during the preceding 48 hours. The air parcel arriving at 1600 experienced slow transport from the southwest during the preceding 12 hours. During the day on July 28 the stationary front moved northward and passed through Tulsa by the next morning. There were mostly southerly surface winds measured throughout the network during July 28. Winds aloft were from the southwest. Both the local back trajectories and the forward trajectories of the urban air parcel (Figures 4.13 and 4.14a) indicate that Vera was not directly influenced by the Tulsa urban air. However, the maximum ozone concentration in the network, 0.116 ppm, was measured at Vera at 1700. Since the maximum ozone concentration measured at Vera was considerably higher than at other stations in the network, it is assumed that Tulsa emissions were responsible for the ozone measured at Vera. Unfortunately, the ozone data from Sperry were missing during the photochemically active portion of the day and thus the advance of the Tulsa urban plume cannot be completely described.

The slow northward transport and limited morning solar radiation on July 28 delayed the first signs of ozone production until hour 1200, when Skiatook measured an ozone concentration that was elevated with respect to the other stations (Figure 4.19). At Vera, elevated ozone concentrations were first measured during the 1400 hour. Both Vera and Ochelata then measured relatively high ozone concentrations until 2000. During hour 2100, Vera measured decreased ozone concentrations, while the ozone concentration at Wynona increased. Southeasterly winds, which may have carried ozone from Vera to Wynona, were measured during hour 2100 at many of the network stations.

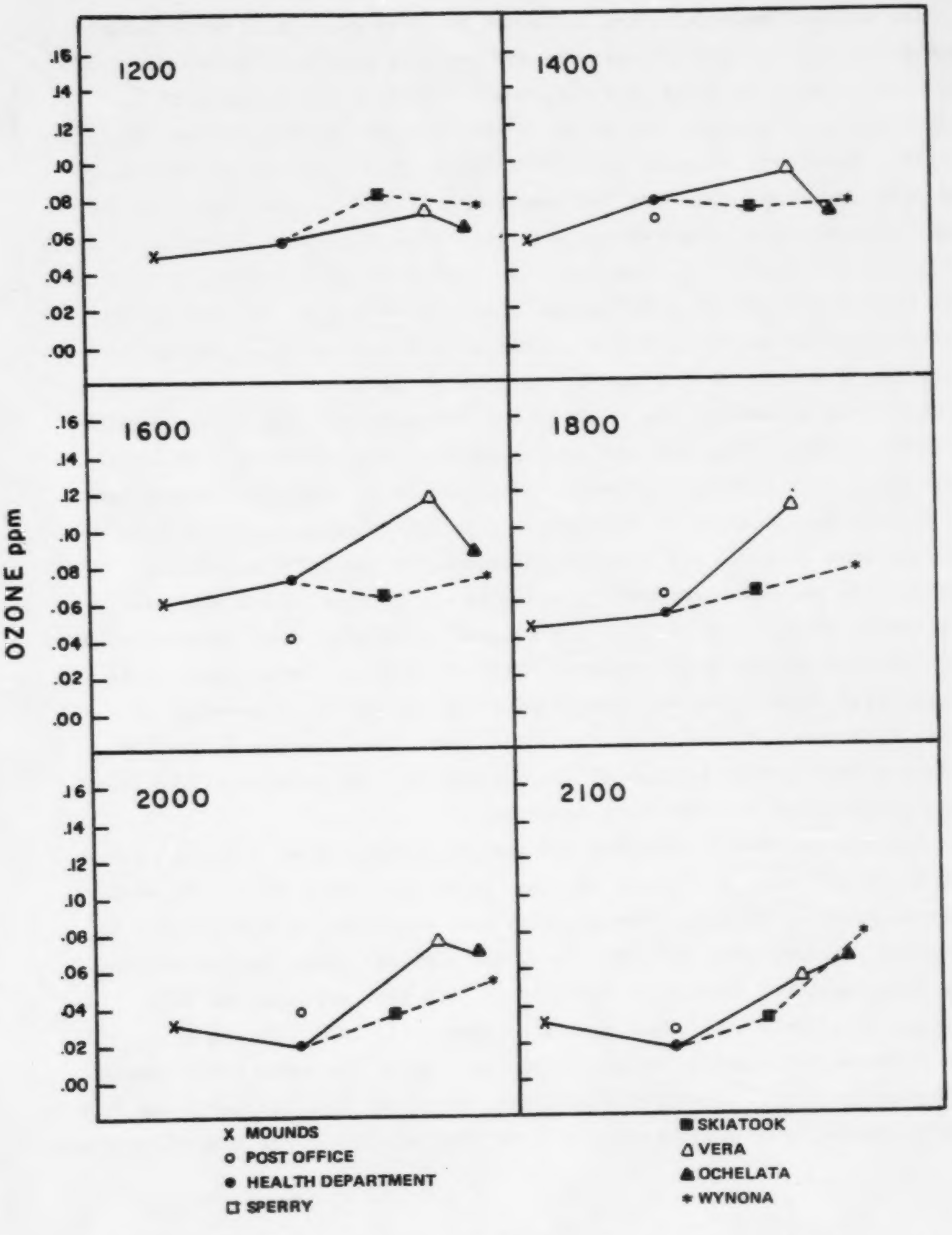


Figure 4.19. Ozone concentration/distance plots for July 28, 1977.

Although July 28 was not an ideal day for ozone formation in Tulsa, the net ozone production of Tulsa can be estimated. Since southerly winds were measured in the monitoring network during most of the day, it can be assumed that Liberty Mounds measured the background influence on Tulsa. The average of the 1000 and 1100 ozone concentrations at Liberty Mounds was 0.043 ppm. The difference between the network maximum ozone concentration of 0.116 ppm measured at Vera and the background ozone concentration is 0.073 ppm which is assumed to represent the net ozone formation of Tulsa for July 28.

### 4.3.4 Analysis of July 29, 1977

The 0700 EST surface weather map shows the position of the stationary front to be immediately north of Tulsa (Figure 4.11e). This front was the major influence on Tulsa on July 29, and it produced partly cloudy skies during the day. There were variable winds measured in the network on this day and the forward trajectories of the urban air parcel (Figure 4.14b) indicate stagnation of the urban air until the late afternoon hours when transport to the south became apparent.

Surface weather maps for every 3 hours for the night of July 28 were examined, and from these maps the time of the frontal passage was found to have occurred between 0300 and 0600. An interesting nocturnal ozone increase was measured at each station in the network at some time during the predawn hours of July 29. Increasing ozone concentrations of this type have been observed elsewhere.(1, 2) It is likely that the frontal passage caused a disturbance that allowed ozone from above the radiation inversion to reach the surface.

In addition to its effect on the cloud cover, the return of the front to the immediate Tulsa area also produced variable winds in the monitoring network. Prior to the time of maximum network ozone at Liberty Mounds of 0.127 ppm at 1700 there was a northeast wind measured at Ochelata. Although the synoptic-scale trajectories indicate that air arrived in Tulsa from the southwest, the local mesoscale trajectories were controlled by the tendency toward northeasterly and northerly winds. Winds aloft were from the north and northwest. During most of the afternoon the Liberty Mounds station was measuring northerly winds, implying that Tulsa emissions were carried to Liberty Mounds during the afternoon.

Although there were overcast skies during the night and scattered or broken cloud cover reported all day long, both solar radiation and temperature reached higher values on July 29 than on July 28 (Figures 4.15 and 4.16). The combination of improved solar radiation, increased temperature, and the northerly winds carrying urban emissions to Liberty Mounds were responsible for the maximum ozone concentration measured during the summer at Liberty Mounds.

During the afternoon hours of July 29, $NO_x$ concentrations at the Post Office site (Figure 4.17) were lower than those usually observed when there was a consistent southerly wind. There were peaks in both the NO and $NO_2$ concentration profiles at the Post Office site at hour 0600 that are indicative of morning traffic emissions. During the remainder of the day and until 2200, the $NO_x$ concentrations at the Post Office were low. There were significant peaks of both NO and $NO_2$ measured at hour 2300. The winds had shifted back to southerly prior to those peaks.

The most striking feature of the network ozone data for July 29 is the diurnal ozone concentration profile for Liberty Mounds (Figure 4.18). The ozone concentration at Liberty Mounds rose rapidly during the morning and was stable through the afternoon until hour 1600. The onset of northeasterly and northerly winds in the afternoon of July 29 was followed by a rapid increase in the ozone concentration at Liberty Mounds. At hour 1600 a very sharp increase of 0.038 ppm occurred and a measured concentration of 0.124 ppm was attained. The 1700 concentration reached 0.127 ppm, which was the maximum measured at Liberty Mounds during the entire summer study. Following a shift to southerly winds, the ozone concentration then fell rapidly and after hour 2000 the concentrations appeared to be approximately what would have been expected had the ozone concentrations decayed from the concentration present prior to the peak.

The second highest ozone maximum of the study occurred for both the Post Office and Health Department sites on July 29. The Post Office station recorded a maximum of 0.112 ppm at 1800. The Health Department station measured a maximum of 0.121 ppm at 1000, much earlier than the time of the daily maximum for either Liberty Mounds or the Post Office. The occurrence of the hour 1800 maximum at the Post Office site is associated with a reversal of the windflow from northeasterly to southerly. Soon after this change in wind direction, the ozone distribution throughout the network became uniform, with slightly higher ozone concentrations being measured at the Wynona site. The reestablishment of southerly winds marks the time that the stationary front no longer had any influence on the Tulsa area.

### 4.3.5 Analysis of July 30, 1977

High pressure centered off the Florida coast was the predominant influence on the weather in Tulsa for this day; clear skies and southerly winds were predominant.

The ozone concentrations measured through the afternoon of Saturday, July 30, at the Liberty Mounds, Post Office, and Health Department sites were typical of background conditions. The afternoon maximum ozone concentration at Liberty Mounds was 0.069 ppm at 1600; however, the maximum daily ozone concentration of 0.070 ppm occurred at hour 2200. At the Post Office site ozone concentrations were less than 0.050 ppm until 1800 when the day's maximum of 0.067 ppm was measured. At the Health Department the maximum ozone was also 0.067 ppm and was measured during hours 1300, 1400, and 1500. Of the stations north of Tulsa, only Vera and Wynona measured maximum ozone concentrations that were significantly above their average daily maximum for the month.

Figure 4.20 illustrates the ozone concentration variability for the network during various hours of the day. Beginning at hour 0600, all of the stations in the network were measuring nearly the same ozone concentrations of approximately 0.025 ppm except for the Post Office, which measured 0.005 ppm. The ozone concentration at this site remained low for the next 2 hours while the ozone measured at the other stations rose. By 0900 Sperry, Vera, and Wynona appeared to be influenced by the urban plume. The Ochelata monitoring station had no data for the 0900 hour. Vera was missing data for the 1000 and 1100 hours but measured the maximum ozone concentration of the day in the network of 0.128 ppm at hour 1200. All of the other stations were measuring concentrations considerably lower than Vera through the afternoon until 1700. Throughout this period, Vera experienced the highest and Wynona the second highest ozone concentrations; however, the data from Ochelata are

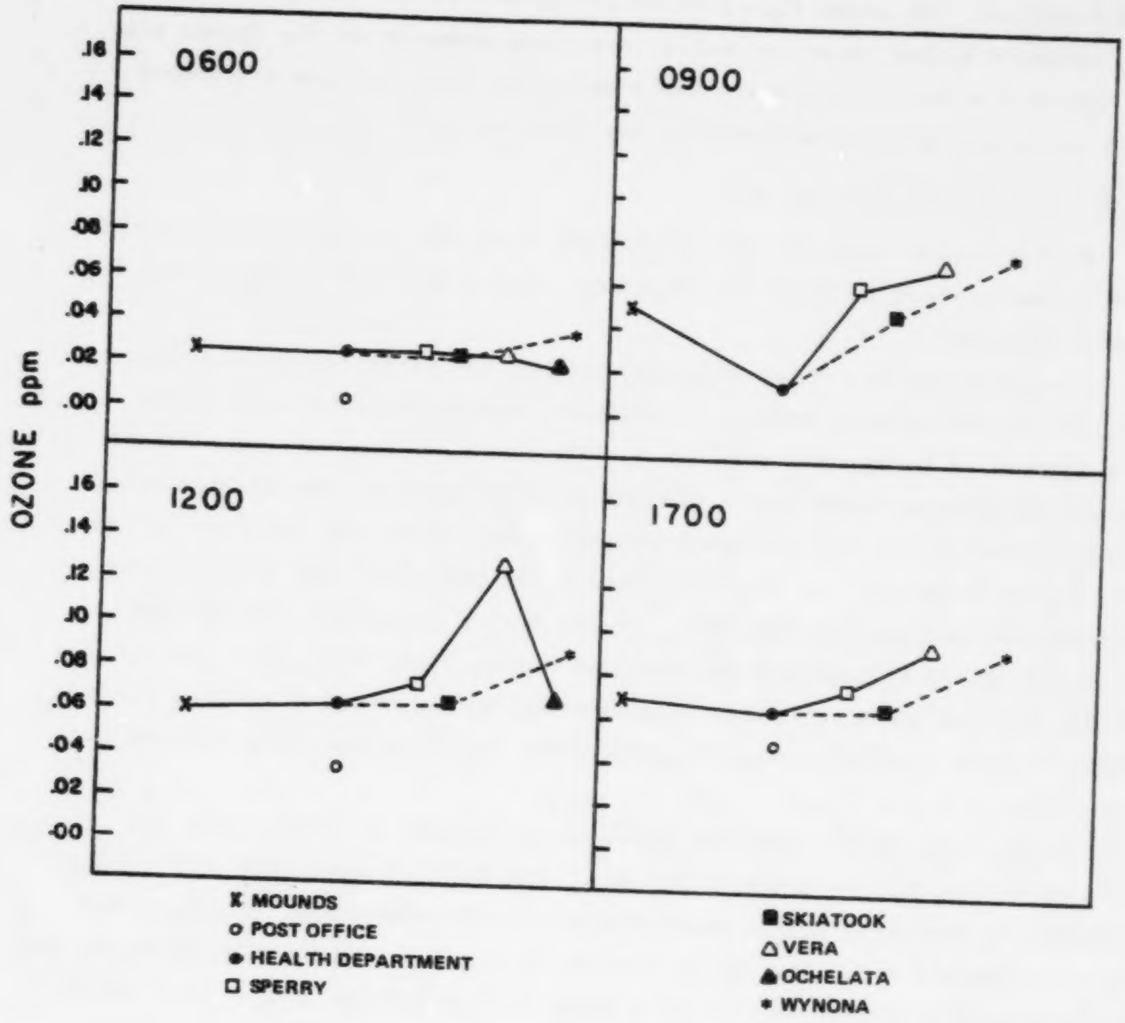


Figure 4.20. Ozone concentration/distance plots for July 30, 1977.

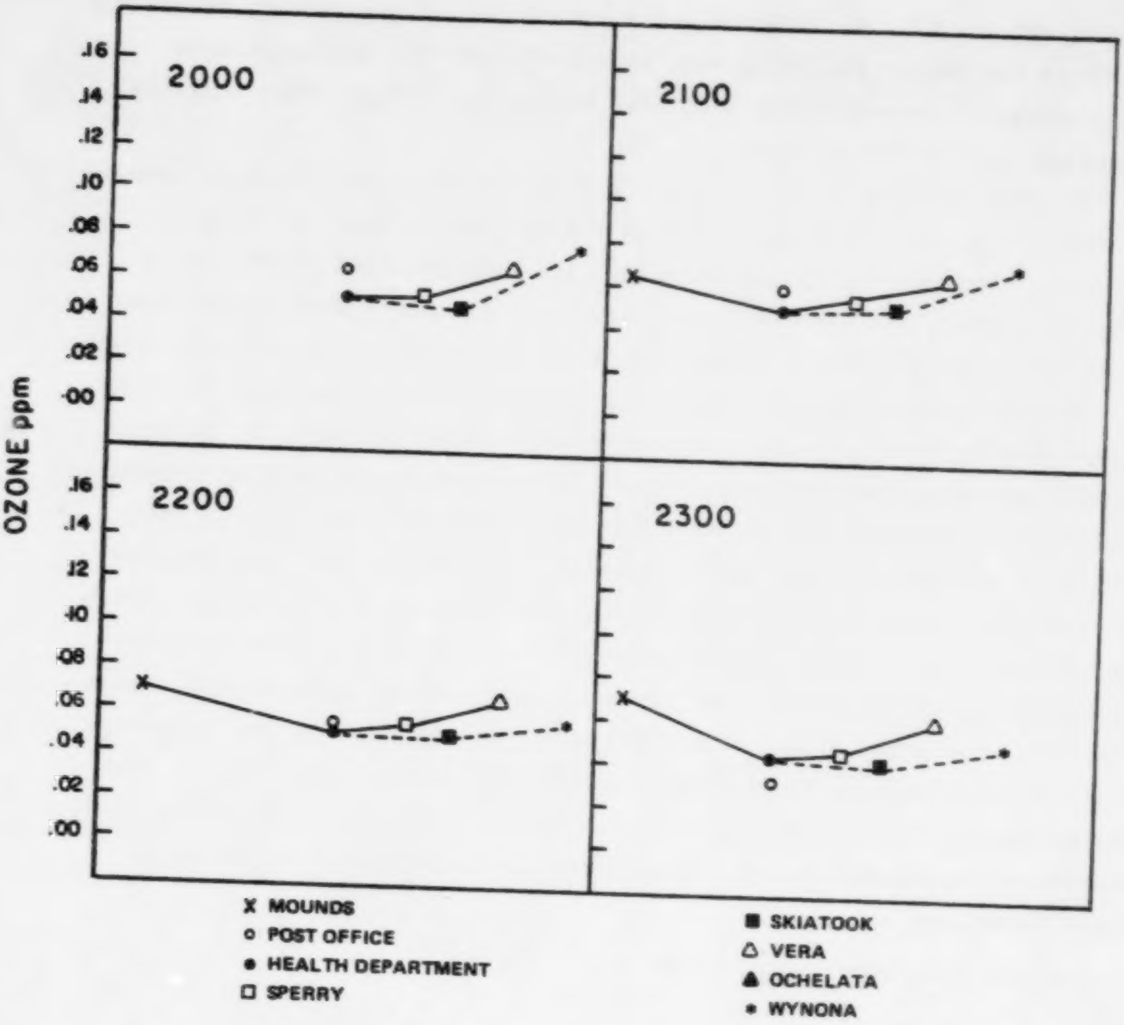


Figure 4.20. Ozone concentration/distance plots for July 30, 1977 (continued).

missing after 1300. At 1700 the ozone concentrations measured at Wynona and Vera were the same. Following hour 1700 until 2100 the Wynona station measured ozone concentrations that were higher than at any other stations reporting data in the network.

At 2000 the wind at Ochelata shifted to northerly and the ozone concentrations at all of the stations except Liberty Mounds began to decrease. The ozone distribution during hours 2200 and 2300 returned to the typical ozone distributions observed in and around an urban area with higher ozone at the outlying stations and lower ozone at sites near or in the urban area.

Because steady southerly winds and uninterrupted solar radiation were measured on July 30 in Tulsa, the net ozone produced by Tulsa can be estimated. An average of the ozone concentrations measured at Liberty Mounds during hours 1000 and 1100 of 0.056 ppm is assumed to represent the background ozone concentration that influenced Tulsa on July 30. The maximum network ozone concentration observed downwind of Tulsa was 0.128 ppm, which occurred at Vera at 1200. It is assumed that this maximum ozone concentration observed in the network was representative of the maximum ozone concentration in the urban plume. Subtraction of the background ozone concentration, which is assumed to be similar at all of the network stations, from the maximum in the network leaves a concentration of 0.072 ppm, which can be considered representative of the net contribution of Tulsa emissions to ozone formation.

## 4.4 AUGUST 2-5, 1977: CASE STUDY

### 4.4.1 Introduction

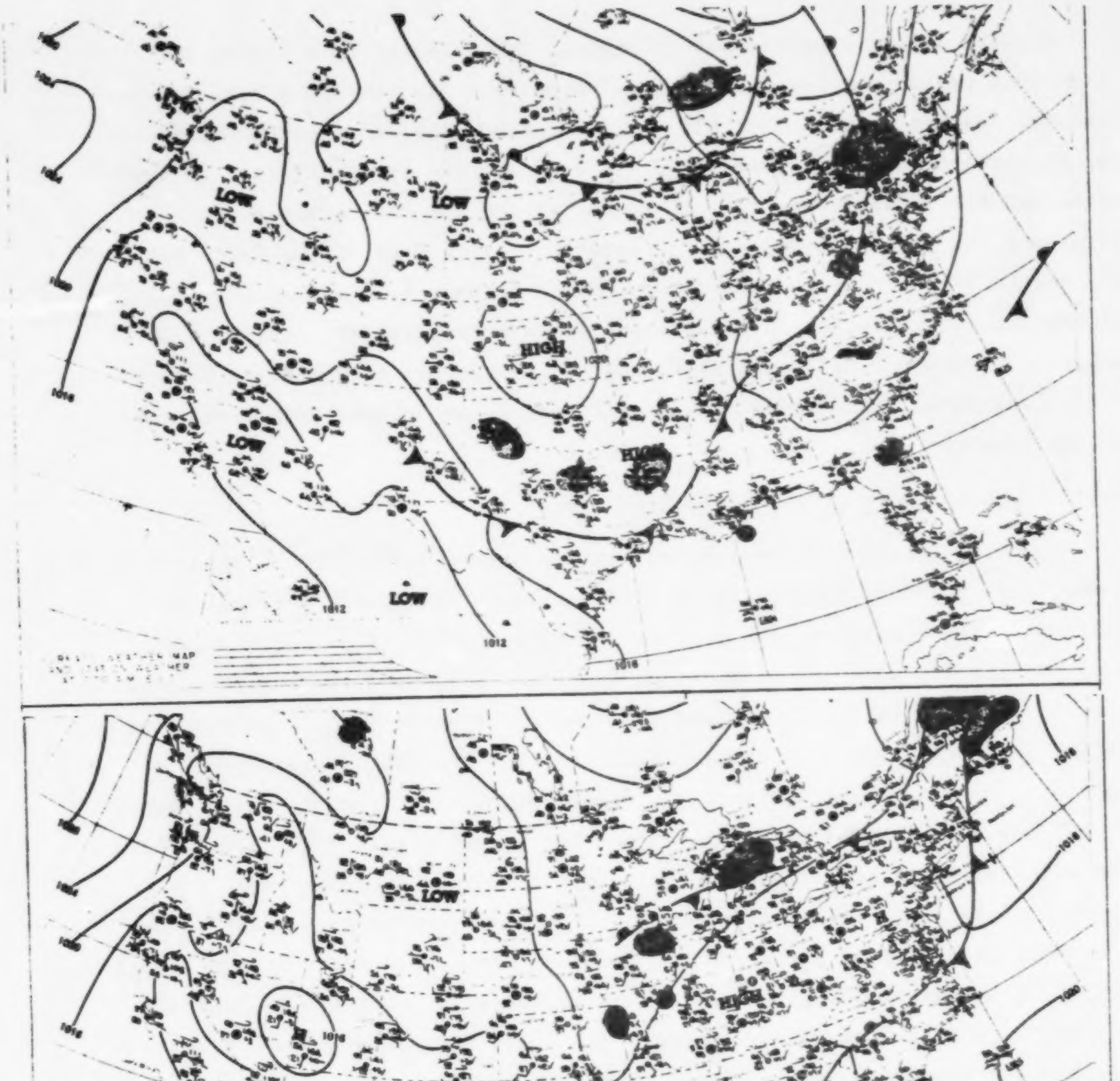
The days August 2-5 (a Tuesday through Friday) were chosen for case study analysis primarily because the highest hourly average ozone concentrations of the entire summer study at Sperry, Vera, and Ochelata of 0.135, 0.151, and 0.114 ppm, respectively, were measured on August 3. August 2 is included because an unusual late afternoon increase in the ozone concentration was observed at each station. August 5 is of interest since the maximum ozone concentration of the entire study period for the Skiatook Lake site (0.120 ppm) was measured on this date.

Figures summarizing the meteorological and chemical data during the case study period are presented below. Figures 4.21a through 4.21f are the National Weather Service 0700 EST surface weather maps for the Unites States for August 1-6, 1977. Figures 4.22 and 4.23 are the synoptic-scale trajectories and the local (mesoscale) trajectories for the case study days. Figures 4.24a through 4.24d are the forward trajectories of the Tulsa urban air parcel for each of the case study days. Figures 4.25 and 4.26 are plots of the diurnal variation in solar radiation and temperature. Figure 4.27 depicts the diurnal variation in NO and $NO_2$ at the two city sites. Figure 4.28 illustrates the diurnal variation of ozone concentrations at each site in the network.

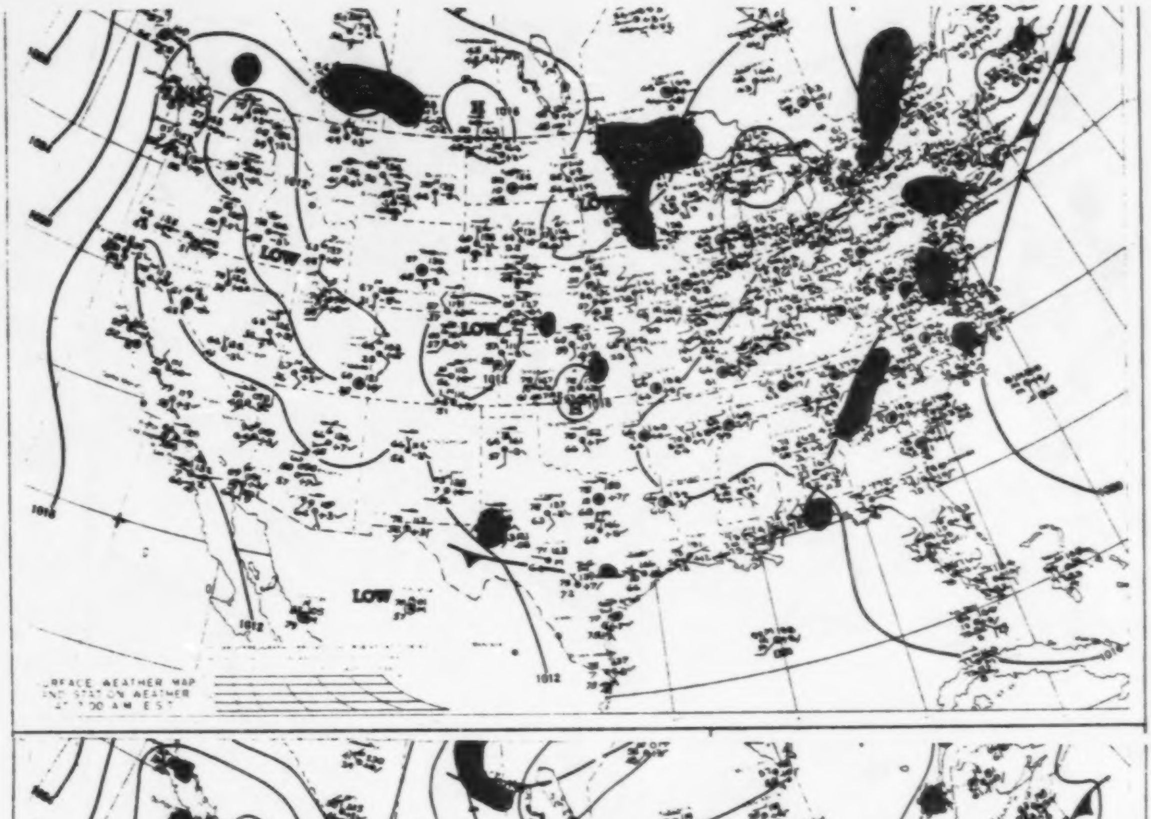
### 4.4.2 General Description of the Case Study

On the 0700 EST surface weather map for August 2 (Figure 4.21) there is a weak high-pressure area centered over the Ohio Valley. As a result of this, easterly winds were observed in Oklahoma at 0700 EST. The synoptic trojectories for both the morning and afternoon arrival times indicate that the air arriving in Tulsa had come from the north, curved in a clockwise motion south of Tulsa, and arrived in Tulsa from the west (Figure 4.22). The local (mesoscale) trajectories indicate air motion from the east except at Liberty Mounds where air arrived from the south (Figure 4.23). Actually, the air arriving at Liberty Mounds also may have come from the east and turned clockwise to arrive from the south. This would be consistent with the other trajectories shown for the northern stations. The foreward trajectories of the urban air parcel, shown in Figure 4.24, show how the winds shifted around in a clockwise motion. The solar radiation (Figure 4.26) reached a maximum mean of 1.5 langleys per minute and there were no extensive interruptions in the solar radiation during the day.

The sum of NMHC concentrations measured during the 6-9 a.m. CDT period on August 2 (listed in Table 4.4) were higher than the August means at all three stations. The acetylene concentrations at each station were not significantly greater than the August means, listed in Table 4.1, while the concentrations of n-butane and other low molecular weight alkanes were higher at each station than the mean concentrations for all August samples.


LOW
LOW
HIGH
HIGH
LOW
LOW
1012
1012
1016
WEATHER MAP
STATION WEATHER
LOW
LOW
LOW
HIGH
H
1016
1012
LOW
1012
WEATHER MAP
STATION WEATHER
A.M. E.S.T.

Figures 4.21a and 4.21b. United States surface weather maps for August 1 and August 2, 1977.


LOW
LOW
LOW
LOW
1012
1016
1012
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.
LOW
HIGH
LOW
LOW
1008
1012
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.

Figures 4.21c and 4.21d. United States surface weather maps for August 3 and August 4, 1977.

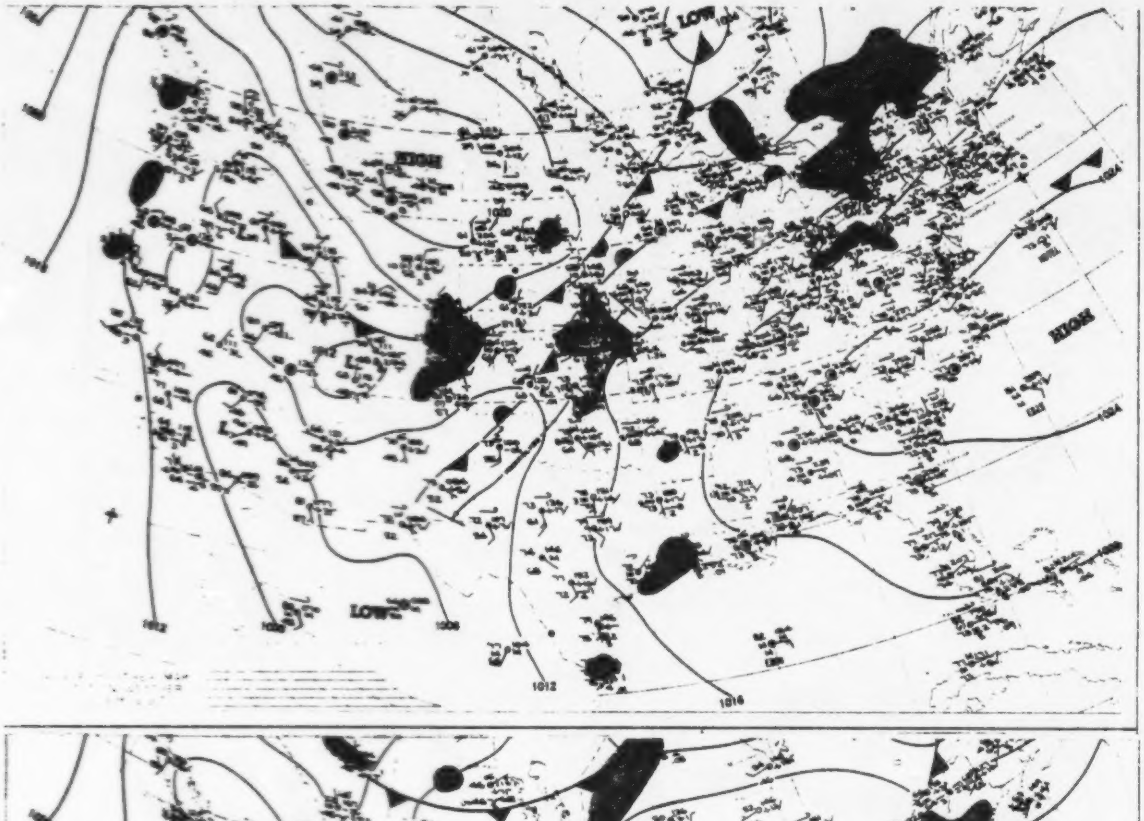

LOW
HIGH
LOW
1012
1016
1020
1024
1008
HIGH
1012
1016
1020
1024
1008
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.

Figure 4.21e and 4.21f. United States surface weather maps for August 5 and August 6 1977.

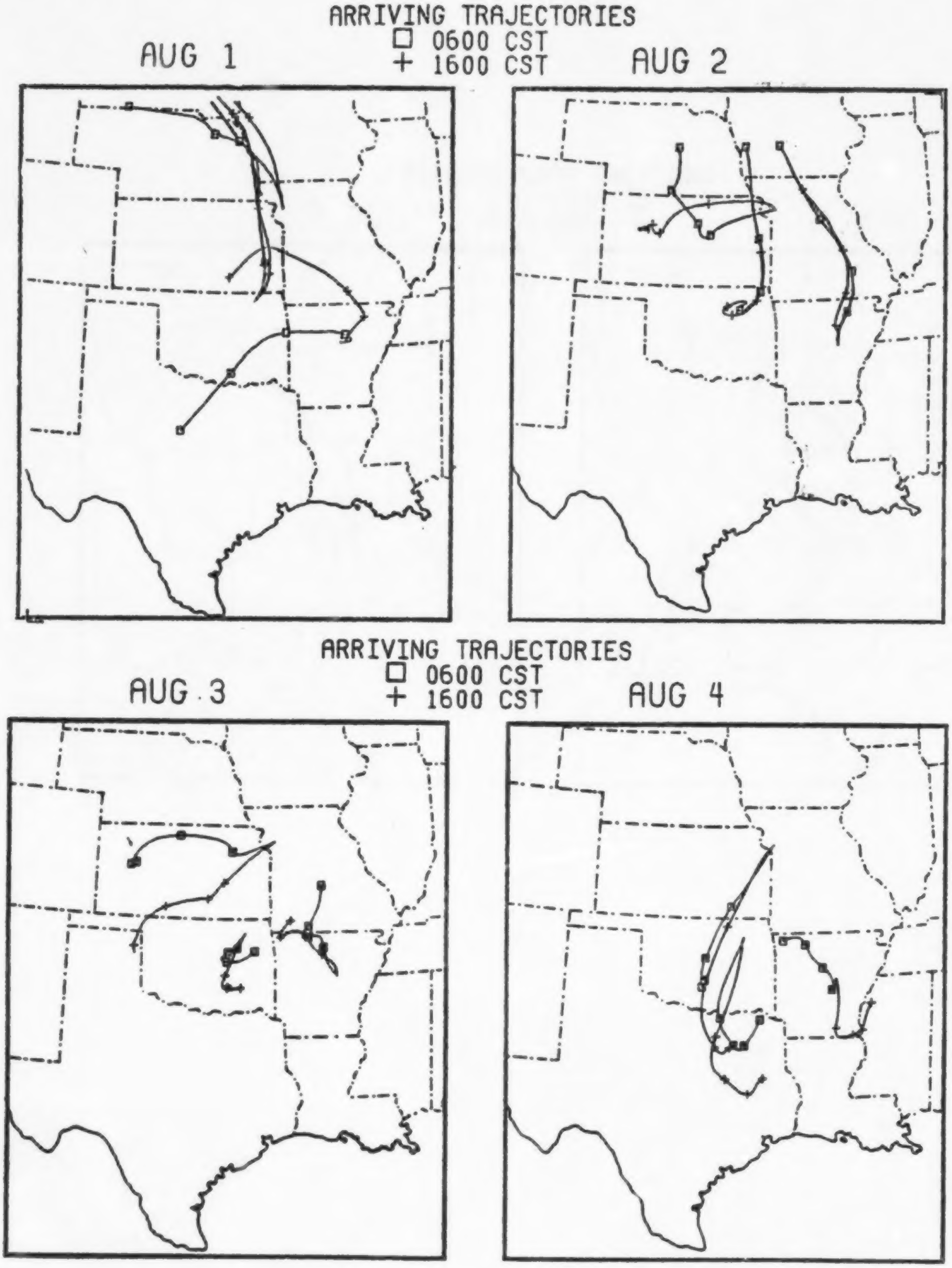

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
AUG 1
AUG 2
ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
AUG 3
AUG 4

Figure 4.22. Synoptic scale trajectories for case study period August 2-5, 1977.

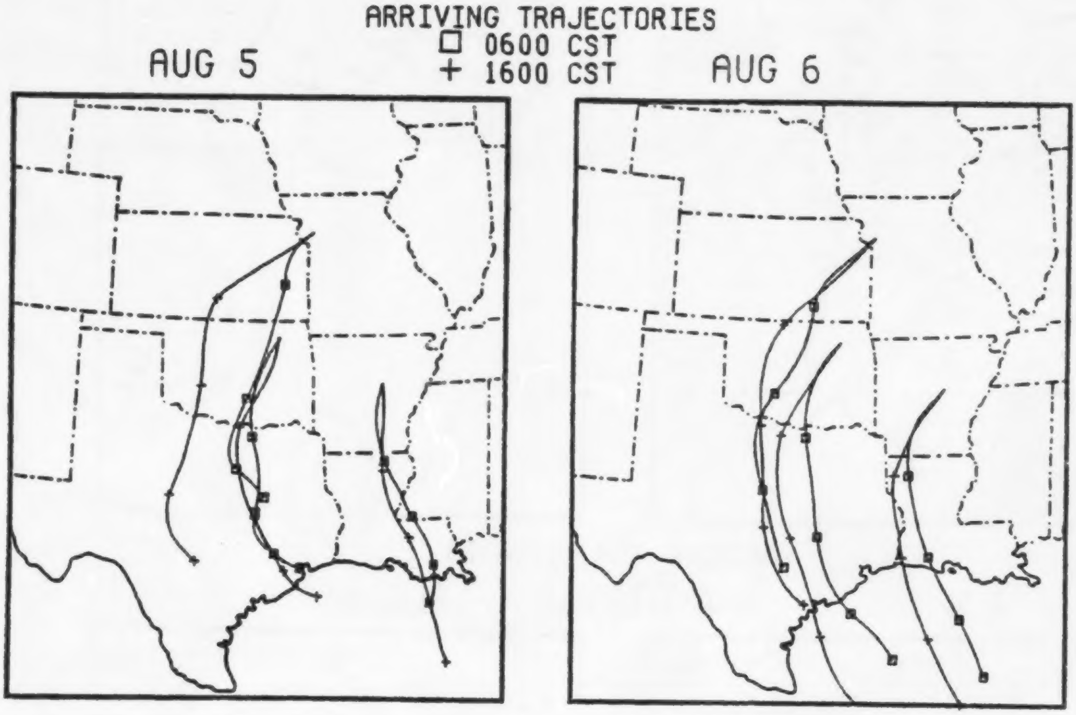
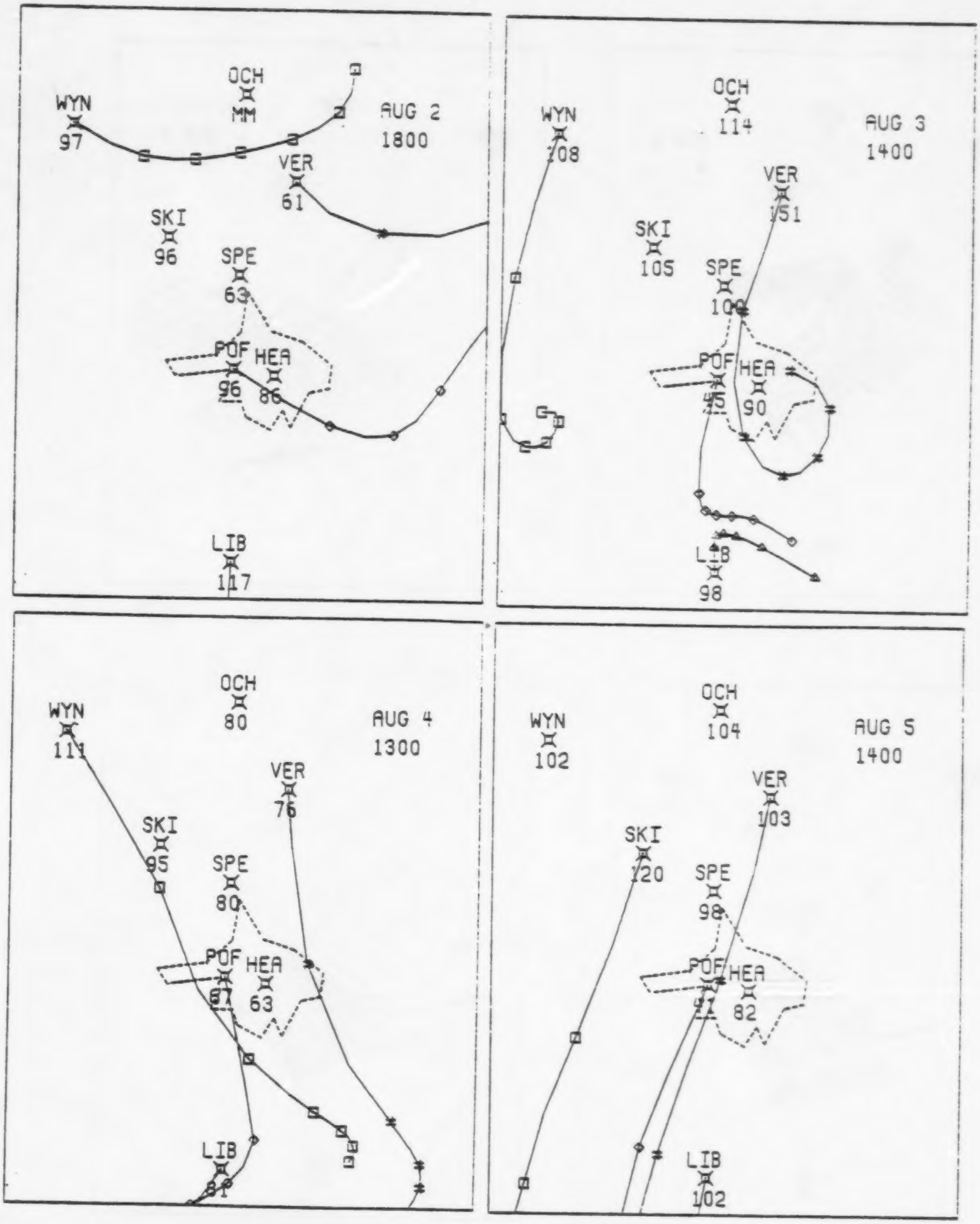

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
AUG 5
AUG 6

Figure 4.22. Synoptic scale trajectories for case study period August 2-5, 1977. (continued).


OCH
MM
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SPE
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114
WYN
108
AUG 3
1400
VER
151
SKI
105
SPE
100
POF
45
HEA
90
LIB
98
OCH
80
WYN
111
AUG 4
1300
VER
76
SKI
95
SPE
80
POF
87
HEA
63
LIB
81
OCH
104
WYN
102
AUG 5
1400
VER
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SKI
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91
HEA
82
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102

Figure 4.23. Mesoscale trajectories for case study period August 2-5, 1977.

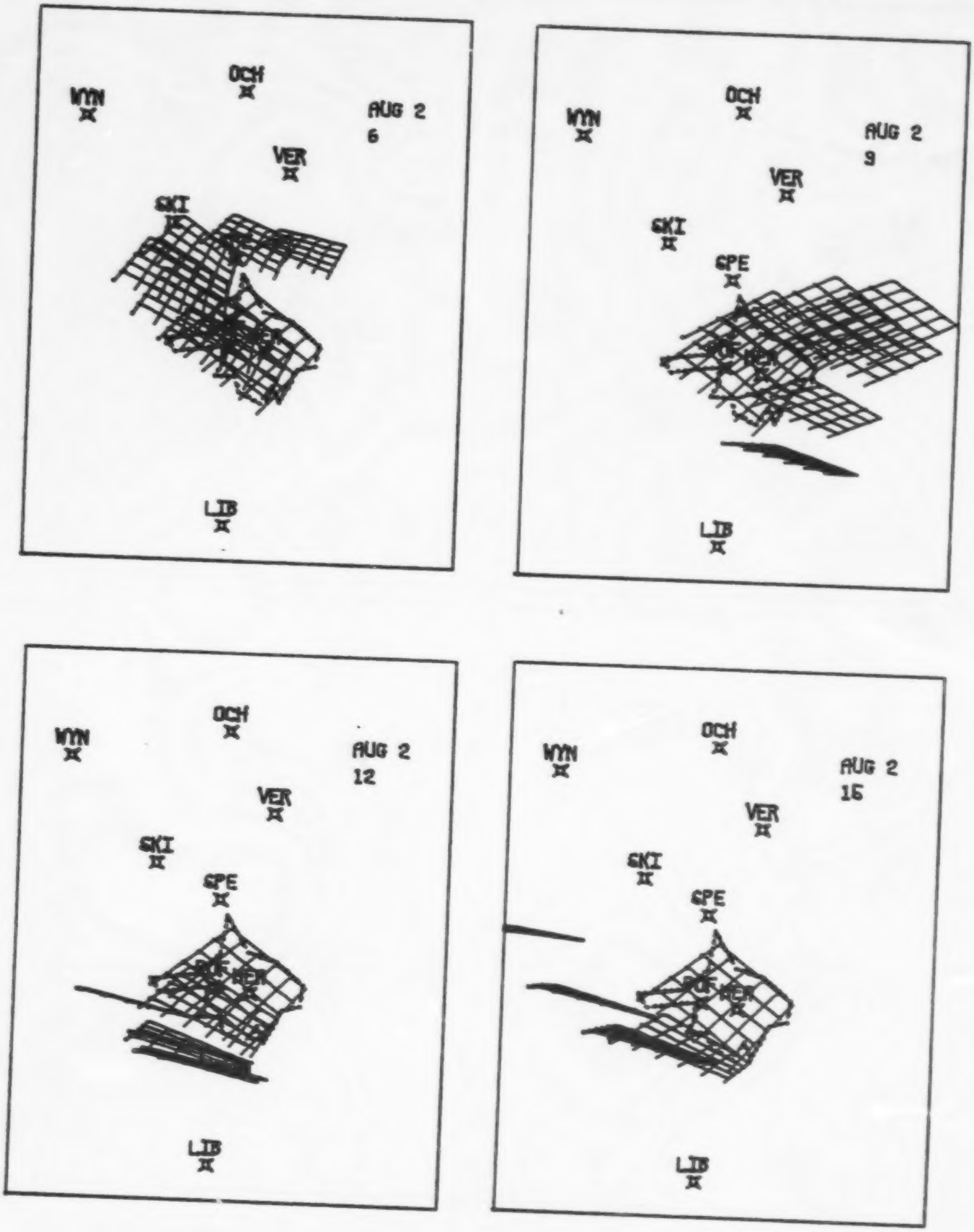
WYN
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Figure 4.24a. Forward air parcel trajectories for August 2, 1977.

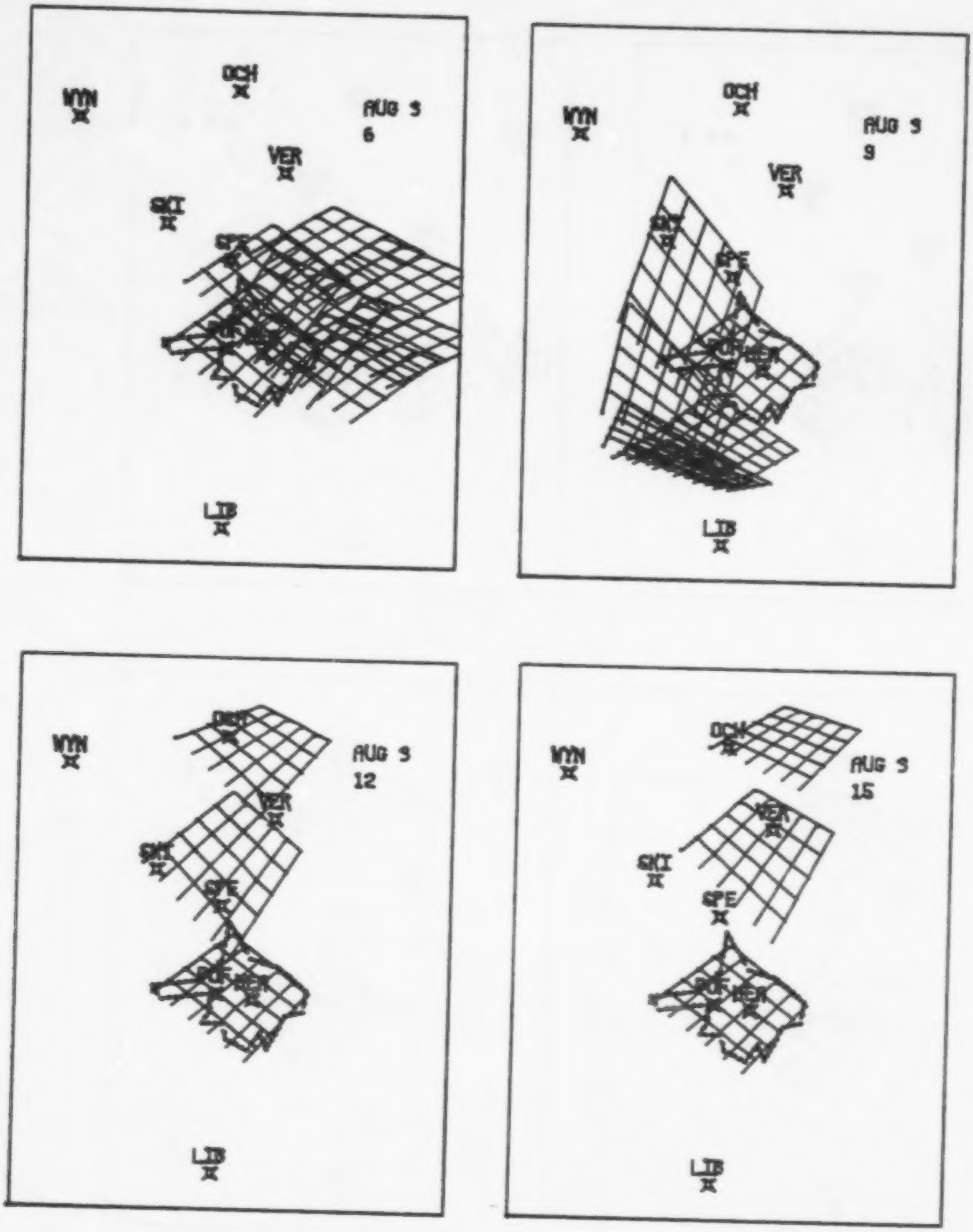

Figure 4.24b. Forward air parcel trajectories for August 3, 1977.

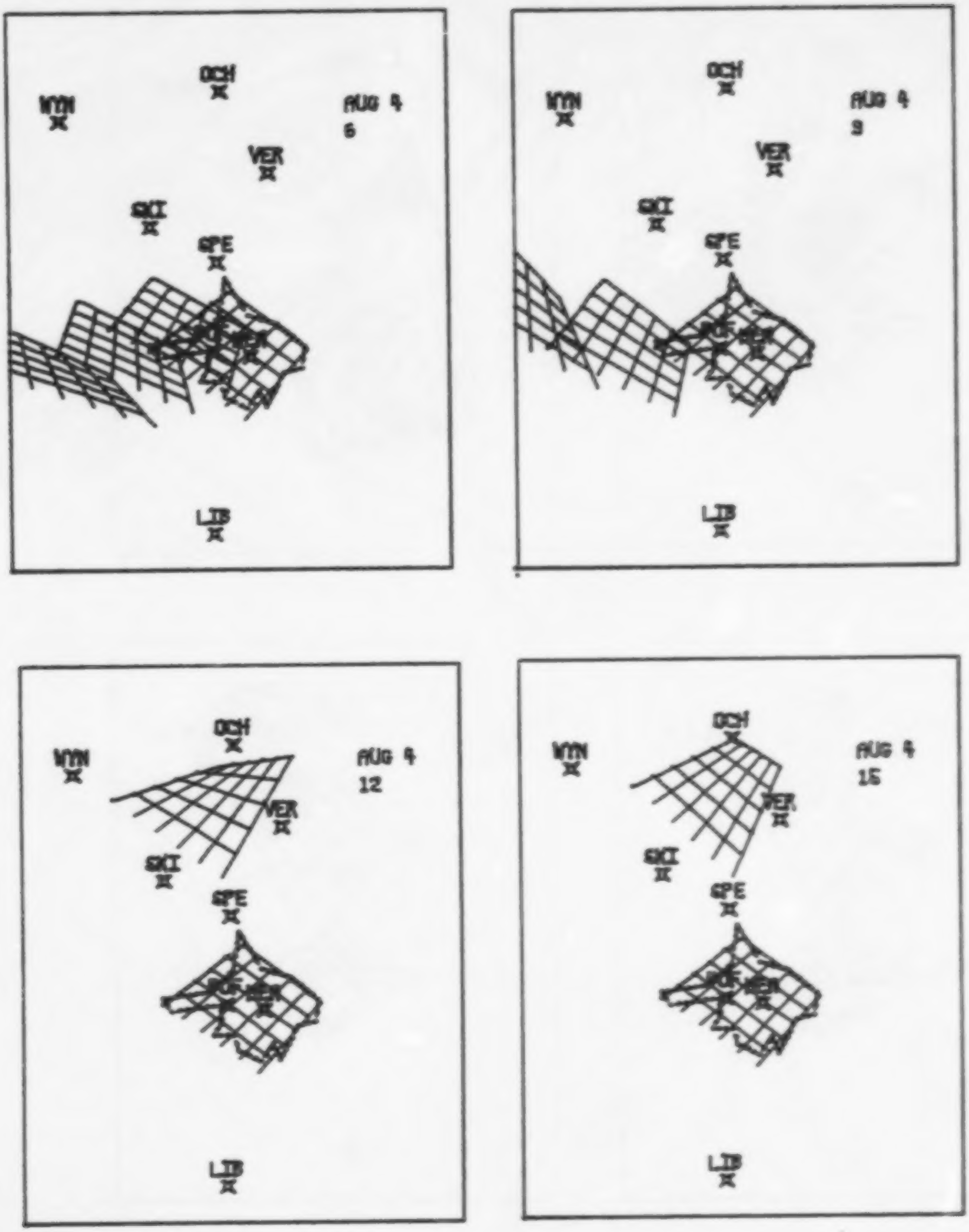
WYN
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Figure 4.24c. Forward air parcel trajectories for August 4, 1977.

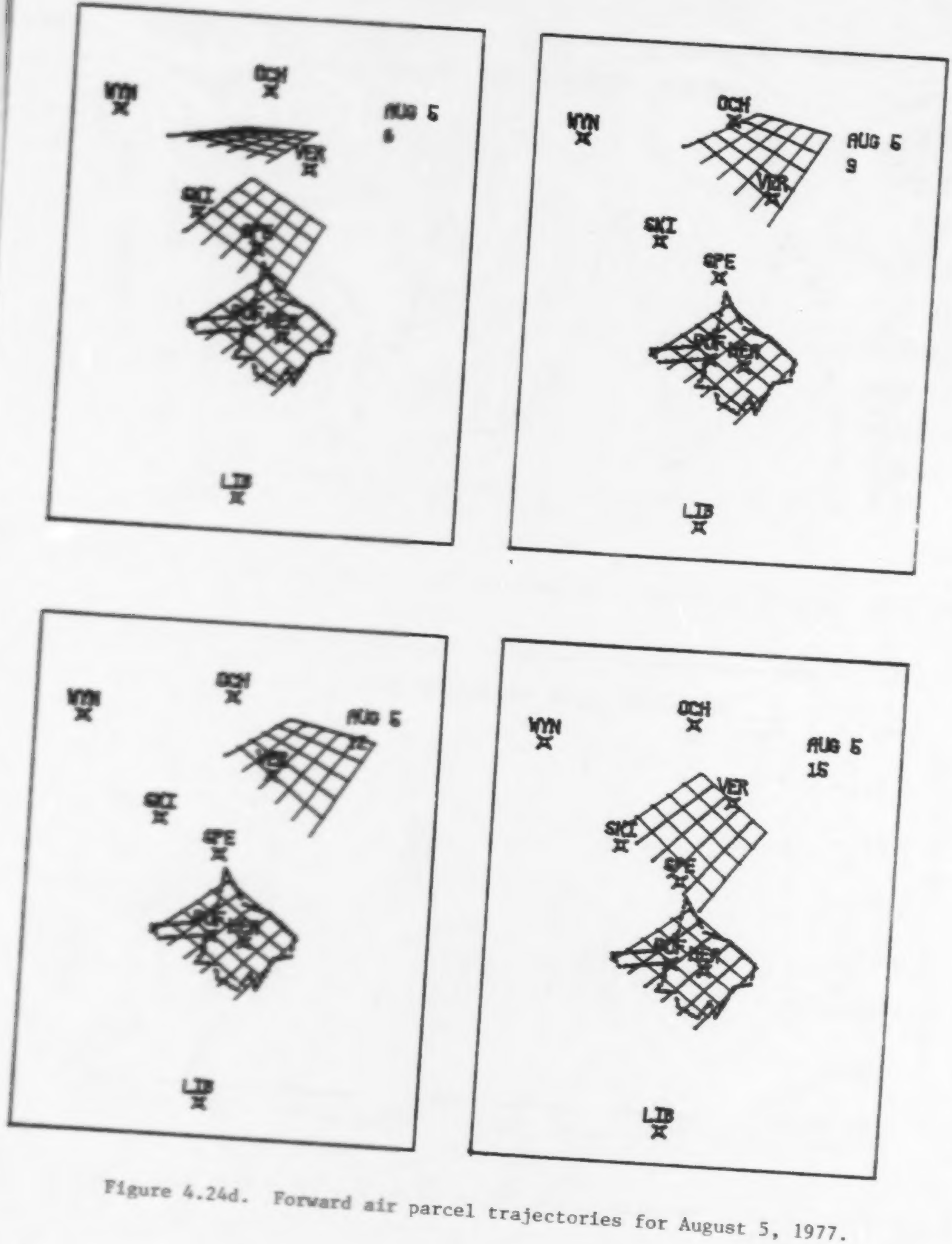


Figure 4.24d. Forward air parcel trajectories for August 5, 1977.

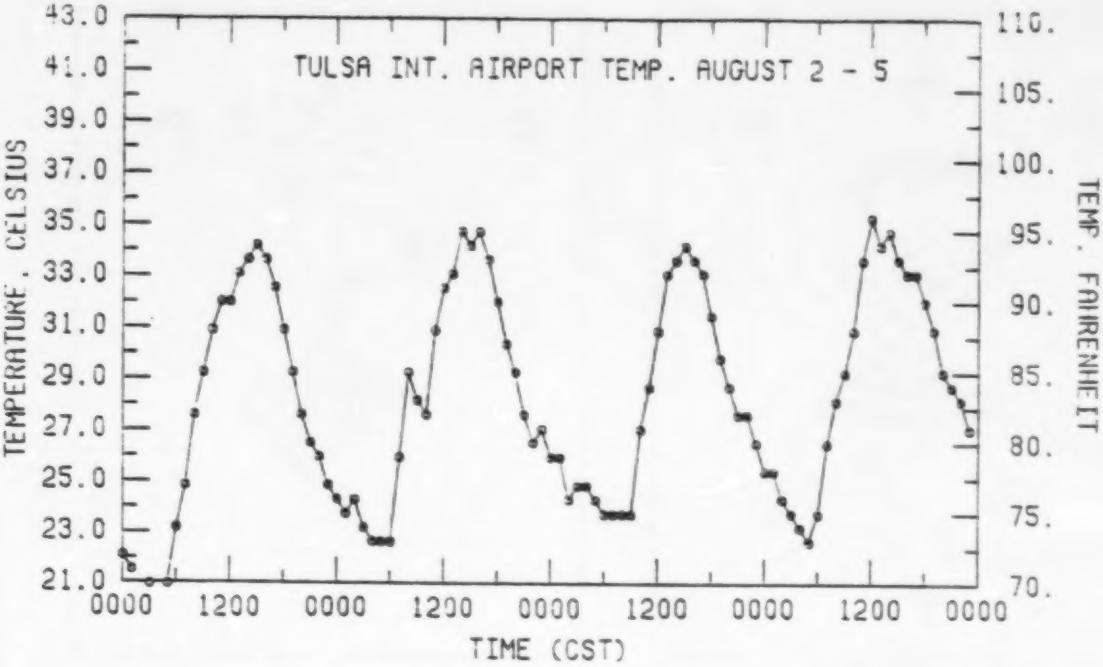


Figure 4.25. Diurnal variation of temperature for the period August 2-5, 1977.

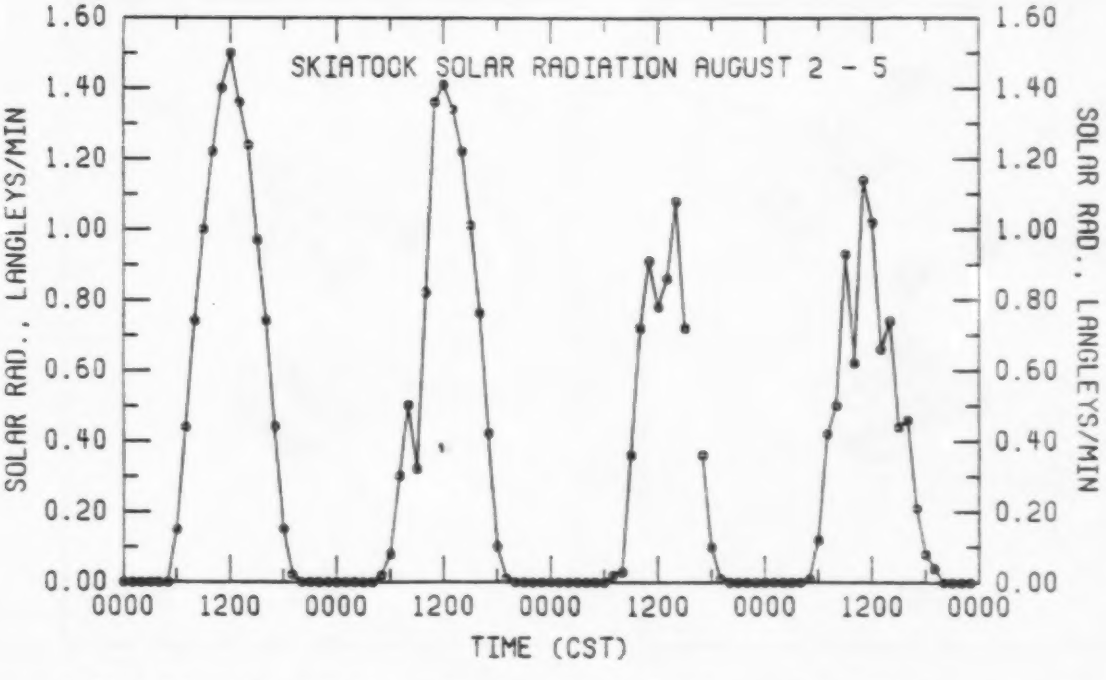


Figure 4.26. Diurnal variation of solar radiation for the period August 2-5, 1977.

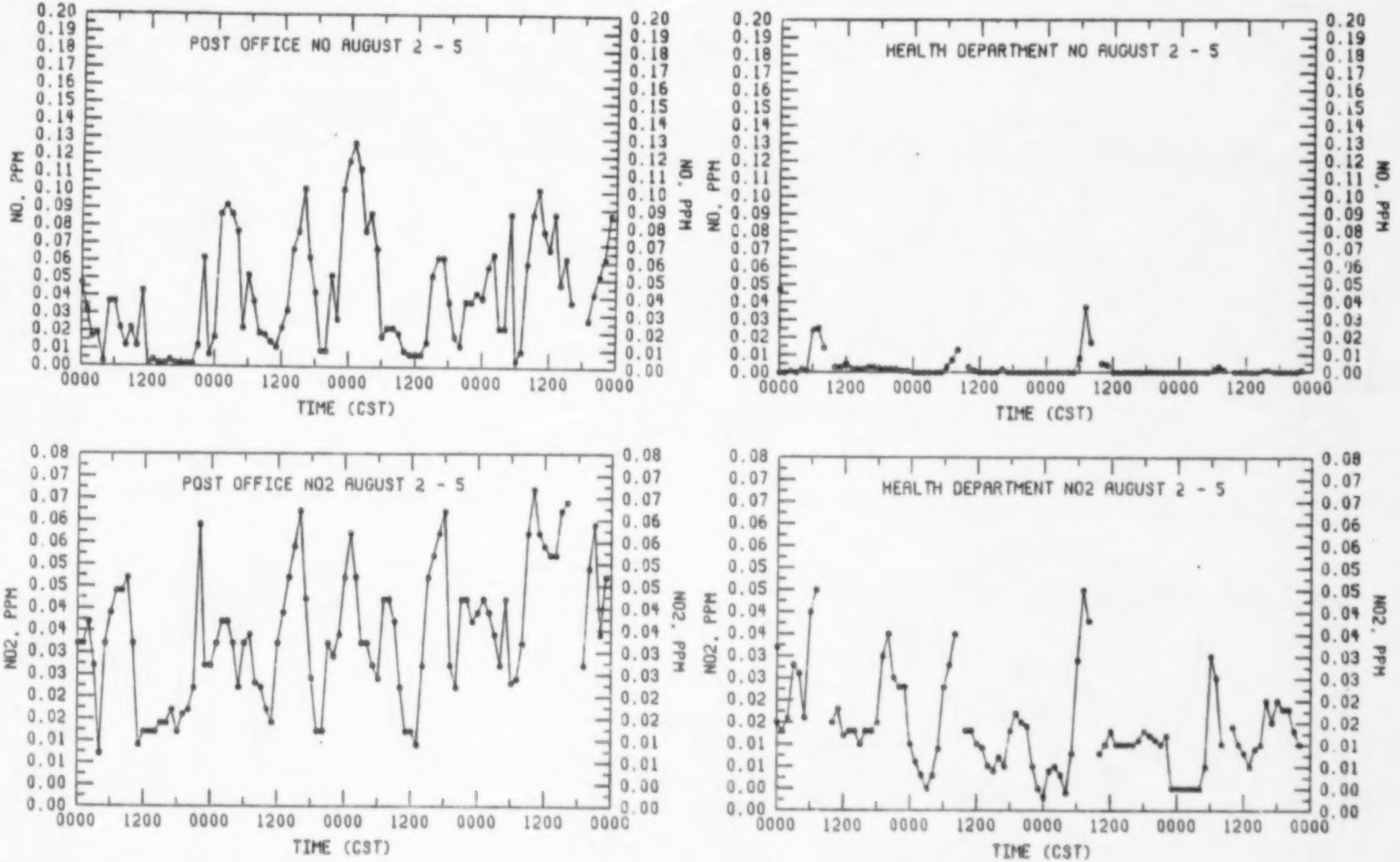


Figure 4.27. Diurnal variation of NO and $NO_2$ for the period August 2-5, 1977.

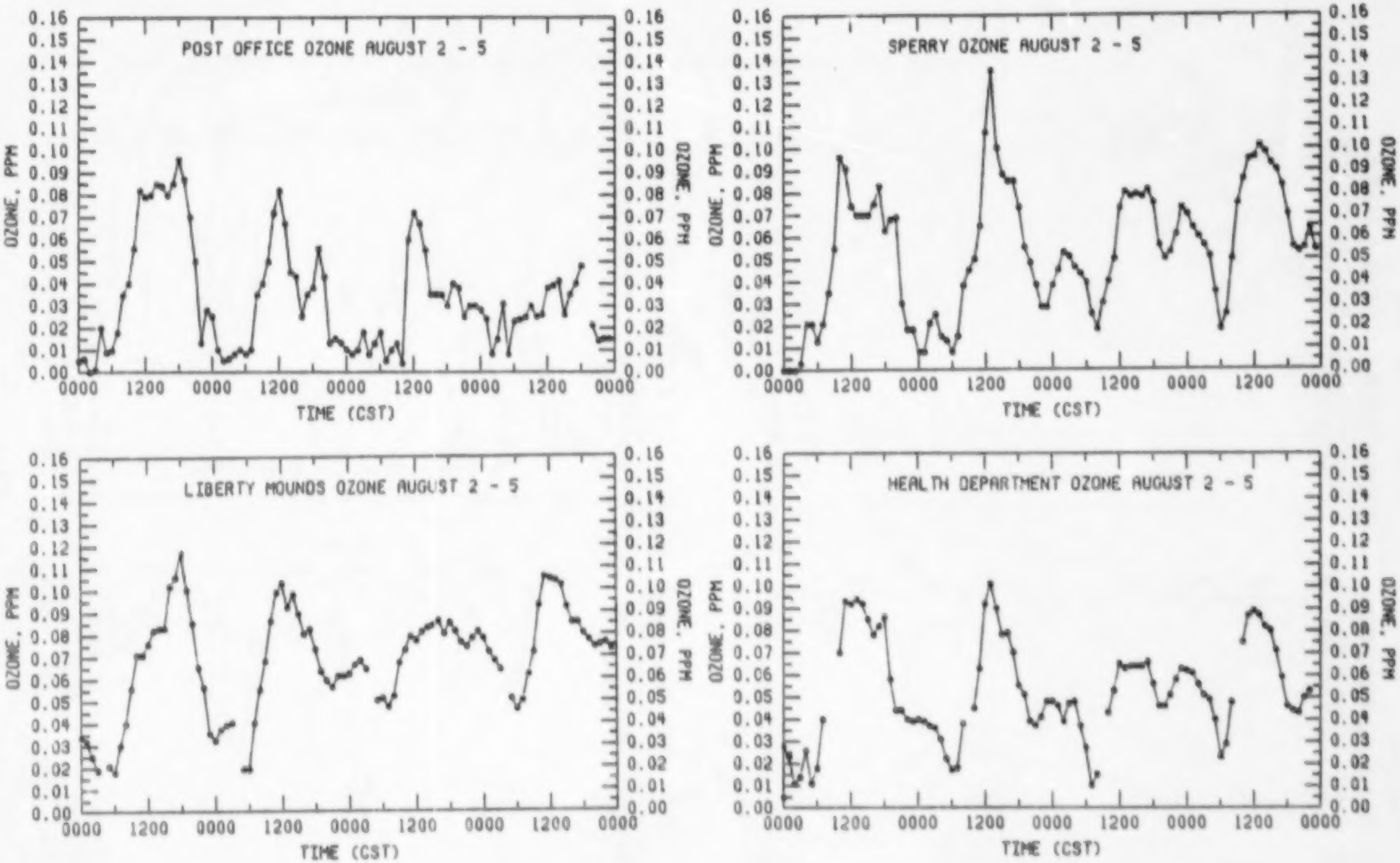


Figure 4.28. Diurnal variation of ozone for the period August 2-5, 1977.

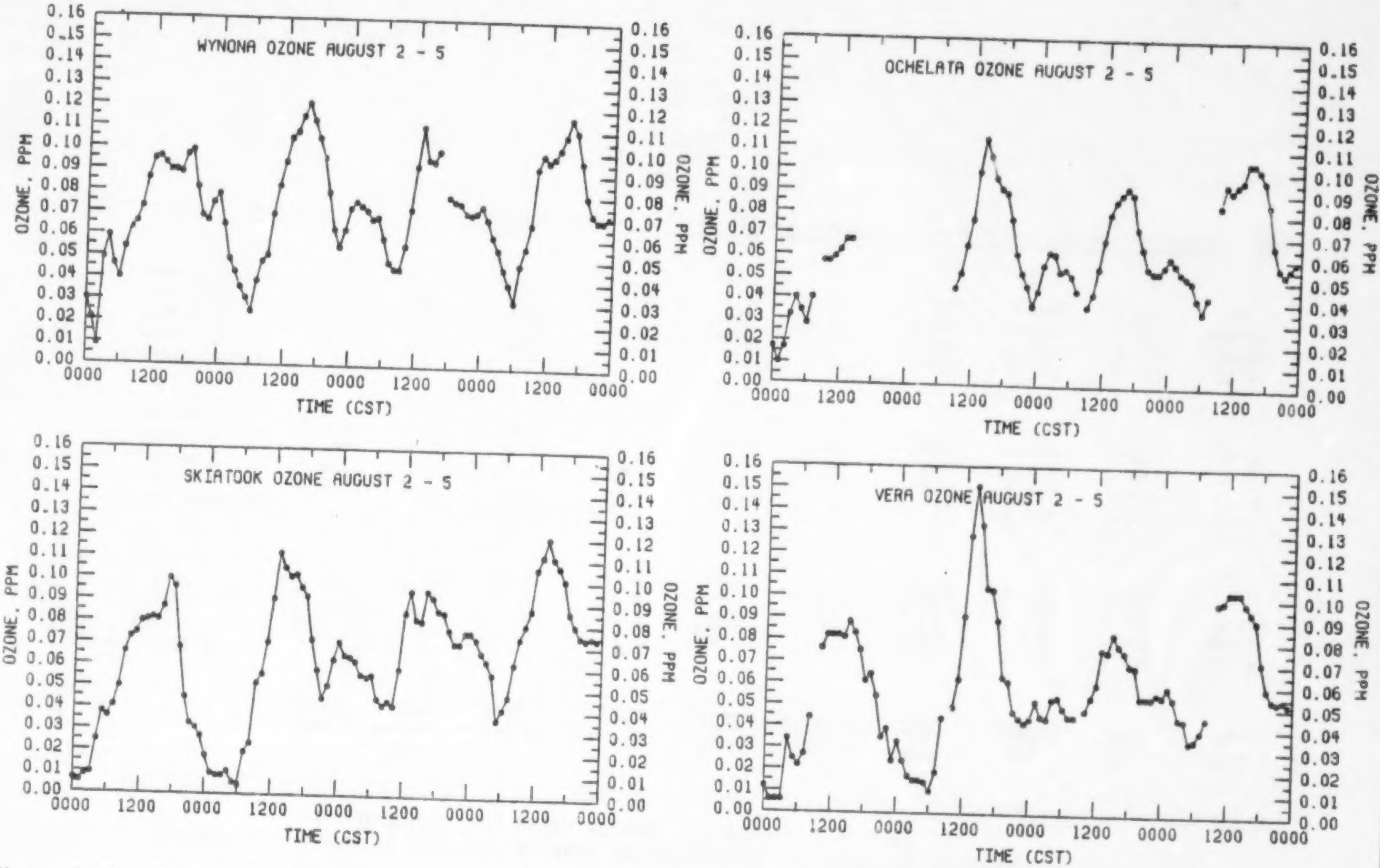


Figure 4.28. Diurnal variation of ozone for the period August 2-5, 1977. (continued).

TABLE 4.4. 0500 TO 0800 CST AVERAGE CONCENTRATIONS OF SELECTED HYDROCARBONS AND OXIDES OF NITROGEN, AND DISTRIBUTIONS FOR AUGUST 2-5, 1977

|  | ΣNMHC ppmC | NMHC Beckman ppmC | ΣAlkenes ppbC | Acetylene ppbC | n-Butane ppbC | % tailpipe emissions | NO ppm | $NO_2$ ppm | $NO_x$ ppm | $\frac{\Sigma NMHC}{NO_x}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Post Office |  |  |  |  |  |  |  |  |  |  |
| August 2 | 0.857 | 1.11 | 97.6 | 15.2 | 129.2 | 27 | 0.032 | 0.043 | 0.075 | 11.43 |
| August 3 | 0.852 | .90 | 89.7 | 17.6 | 135.2 | 32 | 0.037 | 0.034 | 0.071 | 12.01 |
| August 4 | 0.528 | 0.38 | 85.7 | 22.8 | 62.4 | 67 | 0.035 | 0.036 | 0.071 | 7.44 |
| August 5 | -- | -- | 65.4 | 12.2 | 54.4 | -- | 0.033 | 0.035 | 0.068 | -- |
| Health Department |  |  |  |  |  |  |  |  |  |  |
| August 2 | 0.559 | 0.80 | 33.2 | 13.0 | 66.8 | 36 | 0.017 | 0.039 | 0.055 | 10.17 |
| August 3 | 0.343 | 0.08 | 28.7 | 10.4 | 41.2 | 47 | 0.003 | 0.025 | 0.028 | 12.24 |
| August 4 | 0.396 | 0.62 | 36.5 | 20.2 | 35.2 | 79 | 0.015 | 0.032 | 0.047 | 8.42 |
| August 5 | 0.223 | 0.24 | 29.1 | 10.0 | 16.0 | 69 | 0.001 | 0.025 | 0.026 | 8.58 |
| Liberty Mounds |  |  |  |  |  |  |  |  |  |  |
| August 2 | 0.424 | -- | 9.0 | 4.4 | 48.8 | 16 | 0.003 | 0.009 | 0.012 | 35.37 |
| August 3 | 0.209 | -- | 7.0 | 0.6 | 25.8 | 4 | 0.006 | 0.011 | 0.016 | 13.06 |
| August 4 | 0.097 | -- | 4.8 | 1.2 | 14.0 | 19 | 0.003 | 0.005 | 0.008 | 121.50 |
| August 5 | -- | -- | 11.5 | 4.0 | 21.2 | -- | 0.003 | 0.002 | 0.004 | -- |

The 6-9 a.m. CDT average $NO_x$ concentrations were also higher than the August mean at the Health Department and Liberty Mounds but not at the Post Office. The percentage of NMHC contributed by vehicular emissions was not higher than the average at any of the stations.

On the 0700 EST surface weather map for August 3 (Figure 4.21), a small high-pressure cell was indicated just north of the border between Oklahoma and Kansas, and a small cell of low pressure was located over western Kansas. The pocket of high pressure, although small and weak, had an influence on the local winds. The synoptic-scale trajectories for August 3 (Figure 4.22) again show a clockwise turning of the wind from east and south of Tulsa to arrive from the southwest. The trajectory for air arriving at 0600 CST indicates that very slow transport had occurred over the 12 hours preceding the arrival time. The trajectory for air parcel arrival at 1600, however, shows that the wind speeds began to increase and the last 12 hours of the trajectory indicate that there was some air parcel advection from the southwest. The local-scale trajectories (Figure 4.23) for August 3 once again show a definite clockwise shift in the winds. The air parcel that arrived at Vera at 1400 had the highest ozone concentration measured in the entire summer study. This air parcel had remained close to the metropolitan Tulsa area throughout the morning. By 1200 CST the winds had become southerly and the urban air was advected to the north. The forward air parcel trajectories (Figure 4.24) also show the same features. The urban air remained in the Tulsa area and, following 1200, began to experience steady transport to the north.

The solar radiation may also have had an important influence on the ozone concentrations observed at the downwind stations. The maximum solar radiation for the day was approximately 1.4 langleys per minute; however, during the morning hours, until 1000 CST, the solar radiation was limited by cloud cover. Therefore, the morning precursor emissions may have accumulated under stagnant conditions and as northward transport began, the appearance of the sun caused rapid photochemical ozone synthesis.

The 6-9 a.m. CDT average precursor concentrations listed in Table 4.4 were not greater than the August means at any of the measurement sites, except for the sum of NMHC measured at the Post Office, which had a concentration as high as that of August 2. The percentage of hydrocarbons due to vehicular emissions was low in that sample, however, which suggests that the refinery complex may have contributed to that high concentration of NMHC.

A squall line was shown in the immediate Tulsa area on the 0700 EST surface weather map for August 4 (Figure 4.21). There was 0.01 inch of precipitation reported during hour 0800 at the Tulsa International Airport. The synoptic trajectories for August 4 (Figure 4.22) show that steady southerly winds had advected air to Tulsa for approximately 24 hours prior to both of the air parcel arrival times. The local trajectories (Figure 4.23) indicate that the winds in and around Tulsa were southerly to southeasterly, although during the hours surrounding the precipitation there were mostly easterly winds measured in the network. The forward trajectories of the urban air parcel (Figure 4.24) show the influence of easterly winds during the morning hours, and the southerly winds beginning in the afternoon. The solar radiation was relatively low during August 4 with a maximum of approximately 1.1 langleys per minute, which occurred at 1400 CST.

The 6-9 a.m. CDT NMHC concentrations on August 4 at the Post Office and Liberty Mounds were below the mean for August samples, but at the Health Department the morning sample was near the August mean. The percentage of the total NMHC due to vehicular emissions at the Post Office and Liberty Mounds was near the August means as were the 6-9 CDT average $NO_x$ concentrations at those sites. At the Health Department, however, the percentage of NMHC due to vehicular emissions and the 3-hour average $NO_x$ were considerably greater than the August means, implying that a strong traffic source influenced the Health Department. At the Post Office and Liberty Mounds sites, however, increased emissions from traffic sources and industrial sources were likely. The maximum network ozone on August 4 of 0.111 ppm occurred at Wynona. The local trajectory showed the air parcel moving directly over the southwest area of the city and on to Wynona. Therefore, the ozone measured at Wynona on August 4 was likely a direct result of Tulsa emissions.

On the 0700 EST surface weather map for August 5, a stationary front was shown just west of Oklahoma (Figure 4.21). This front did not move into the Tulsa area on August 5, but a large area of cloudiness ahead of the front caused the solar radiation to be low (less than 0.8 langleys per minute) most of the day.

The synoptic-scale trajectories (Figure 4.22) show winds from the southwest for approximately 24 hours preceding air parcel arrival in Tulsa at both arrival times. The local scale backward trajectories also show steady southerly winds in Tulsa (Figure 4.23), as do the forward urban air parcel trajectories (Figure 4.24).

The concentrations of selected hydrocarbons and oxides of nitrogen (Table 4.4) were less than the August average at the Post Office and near the August average at Liberty Mounds. All of the hydrocarbon species from the Health Department sample were lower than the average August values. At each of the three stations, the 3-hour average $NO_x$ concentration was near the August mean. The maximum ozone concentration of the entire summer study at Skiatook of 0.120 ppm was measured at 1400 on August 5. Inspection of both sets of local trajectories implies that the refinery area may have directly influenced the Skiatook site on August 5.

### 4.4.3 Analysis of August 2, 1977

A disorganized area of high pressure was over the eastern States on the morning of August 2 (Figure 4.21b). Throughout the day a frontal area remained stationary along the Gulf Coast. This front also caused other synoptic systems to stall, and the weather in Tulsa on August 2 was not directly influenced by any major synoptic influences. There were sunny skies most of the day and light variable winds as shown by both the synoptic-scale trajectories (Figure 4.22) and the forward urban air parcel trajectories (Figure 4.24a). The concentrations of ozone precursors measured at the urban sites and at Liberty Mounds on August 2 were considerably higher than the average concentrations during August. The ozone concentrations increased to values above 0.08 ppm by midday at each station except Ochelata. The ozone concentrations measured before the midafternoon hours are assumed to have been generated as a result of plentiful sunlight (1.5 langleys per minute at hour 1200), and the lack of large-scale air parcel advection. The maximum daily ozone concentrations at each of the monitoring stations except the Health Department, Sperry, and Ochelata sites occurred at or after hour

1500. The ozone data after hour 1400 were missing at Ochelata, and at the Health Department and Sperry the ozone concentrations rose to secondary peaks after 1500. The maximum ozone in the network of 0.117 ppm occurred at hour 1800 at Liberty Mounds. Throughout the network the winds were from the south during the late afternoon hours. Tulsa International Airport reported cumulonimbus clouds to the south late in the day. Since the late afternoon increase in the ozone concentrations was network-wide, it is likely that the ozone was brought to the surface by the downdrafts of large cumulonimbus clouds from mid-tropospheric altitudes. Data from the 1800 CST Oklahoma City rawinsonde indicate that there were variations in wind direction with height: 190° at 392 m (1286 ft); 97° at 762 m (2500 ft); 349° at 2298 m (7537 ft). Due to the possible influence of ozone downdrafting, the net ozone production as a result of Tulsa emissions was not calculated for this day. The cloud activity was south of Tulsa and the greatest increase in the ozone concentration occurred at the southern site, Liberty Mounds. The southerly winds could have pushed the ozone-rich air into and north of the urban area causing some dilution. Urban NO emissions could also have served to deplete the ozone concentrations at the stations in and north of the city.

### 4.4.4 Analysis of August 3, 1977

A stationary front remained near the Gulf Coast through August 3, and a ridge of high pressure developed east of Oklahoma. High pressure and the continued stagnation of synoptic systems due to the stalled front caused stagnant conditions in Tulsa. The synoptic trajectories showed very little motion of air in or around Tulsa. The sky was overcast during the morning and did not clear until hour 1000. In addition, southerly winds were established late in the morning as shown by both the local back trajectories (Figure 4.23) and the forward urban air parcel trajectories (Figure 4.24b).

The urban air parcel in which the maximum ozone concentrations were measured remained in the urban area until hour 1300 (Figure 4.23). Therefore, urban emissions of precursor species throughout the morning may have been available for ozone production on August 3. The solar radiation strengthened and northward transport began at approximately the same time. The conditions of accumulated ozone precursors and sudden availability of strong sunshine produced a situation very favorable to ozone production.

The maximum ozone concentrations of the entire summer at Sperry, Vera, and Ochelata were measured on August 3. At Sperry the maximum ozone concentration of 0.135 ppm occurred during hour 1300, and at Vera and Ochelata maximum ozone concentrations of 0.151 and 0.117 ppm, respectively, occurred during hour 1400. The maximum ozone concentration of 0.151 ppm at Vera was the highest hourly average ozone concentration measured in the network during the entire summer.

The background ozone concentration determined by averaging the 1000 and 1100 ozone concentrations was 0.093 ppm at Liberty Mounds. It is likely that this relatively high background ozone concentration resulted from several days of ozone synthesis within the stagnated air mass. It is again assumed that this background ozone concentration was similar at all of the network stations, although the reliability of this estimated background influence could not be determined because ozone measurements above the height of the nocturnal inversion were not available. During the late morning hours, the ozone concentrations at Liberty Mounds were changing rapidly. The fact that the ozone concentrations increased throughout the morning at Liberty Mounds until the daily maximum of 0.103 ppm, which was measured at 1200 CST, also raises questions about the reliability of using Liberty Mounds data as an estimate of the background ozone concentration. The Wynona site appears to be more like a background site on this date and an average of 0.076 ppm ozone occurs during hours 1000 and 1100. The maximum network ozone concentration on August 3, which was also the maximum ozone concentration of the entire summer study, was 0.151 ppm and was measured at 1400 at Vera. The difference between the maximum observed ozone concentration at Vera and the estimated Wynona background concentration is 0.075 ppm and is assumed to represent the net ozone production caused by Tulsa emissions on August 3. The data suggest that the maximum ozone concentration measured downwind of Tulsa during the summer of 1977 was produced by the combination of a large background contribution and conditions that were favorable, both meteorologically and chemically, for ozone synthesis.

### 4.4.5 Analysis of August 4, 1977

On August 4 the stationary front that had held up synoptic movement in the mid-United States was no longer present. High pressure centered over the Atlantic Ocean off the North Carolina coast controlled the weather in Tulsa. There were, however, small local systems that influenced Tulsa, notably a squall line that gave cloudy skies throughout the day and 0.01 inch of precipitation during hour 0800. The synoptic-scale trajectories (Figure 4.22) indicate that southerly winds were present in Tulsa during August 4, and the local trajectories (Figure 4.23) indicate a steady southeast windfield in Tulsa. The forward urban air parcel trajectories (Figure 4.24c) show air movement to the west during the morning, followed by northerly transport during the afternoon.

Increasing ozone concentrations were measured during the night of August 3 at each station in the network. These nocturnal ozone increases were more prevalent at the stations north of Tulsa than in the city or at Liberty Mounds. The squall line in its development and movement could have set up a disturbance that allowed ozone to be mixed down to surface from above the nocturnal inversion, causing this network-wide ozone increase.

The maximum network ozone concentration on August 4 of 0.111 ppm was measured at Wynona during hour 1300. The local back trajectories (Figure 4.23) indicate that the air in which this ozone was measured had originated from the urban area approximately 2 hours earlier. While the maximum ozone concentration north of Tulsa most often occurred at Vera, the steady southeasterly winds on August 4 caused the Tulsa emissions to be transported to Wynona, and Vera was influenced by rural air.

The net ozone production can be estimated for August 4 by assuming that the network maximum ozone concentration of 0.111 ppm observed at Wynona approximated the maximum ozone concentration in the Tulsa urban plume. As before, the average of the 1000 and 1100 ozone concentrations at Liberty Mounds, 0.076 ppm, was considered to represent the background influence on Tulsa. The difference between the maximum ozone concentration and the background ozone concentration of 0.035 ppm is assumed to be the net ozone production of Tulsa on August 4. Because the morning precursor concentrations were not abnormally low, it is assumed that the low availability of sunlight was primarily responsible for the low amount of ozone produced by Tulsa on August 4.

### 4.4.6 Analysis of August 5, 1977

On August 5 the weather in Tulsa was dominated by the large high-pressure area off the coast and by a cold front northwest of Tulsa. The front never reached Tulsa, but a low-pressure trough west of Tulsa that took on frontal characteristics did produce overcast and cloudy conditions in Tulsa. The winds were southerly and, for the first time during this case study, steady regional-scale transport was indicated by the synoptic-scale trajectories (Figure 4.22). Strong southerly winds were also indicated by the local trajectories. Lower than normal morning concentrations of both acetylene and n-butane were measured at the Post Office and Health Department sites. The total NMHC was considerably below the average value for August at the Health Department; the sample was not complete at the Post Office.

Liberty Mounds once again measured a very high maximum ozone concentration of 0.106 ppm, which could not be attributed to Tulsa emissions because southerly winds were present all day. The maximum ozone in the network of 0.120 ppm was measured at Skiatook at 1400. This was also the maximum ozone concentration of the summer at Skiatook.

The cause of the high ozone at Skiatook on August 5 cannot be explained from the available data because the local trajectories do not indicate a direct influence of Tulsa on the Skiatook station. The ozone concentrations at Skiatook and Wynona, however, were greater than at the other stations north of Tulsa. It is possible, therefore, that there was a nearly constant contribution of ozone at each station north of Tulsa that perhaps resulted from transport from Oklahoma City. It is possible that NO emissions from Tulsa depleted the ozone measured at Sperry, Vera, and Ochelata relative to Skiatook and Wynona. The lack of strong sunshine may have caused a situation that led to very little ozone synthesis north of Tulsa, and the net effect of Tulsa on August 5 was to remove ozone via titration reactions.

## 4.5 SEPTEMBER 2 AND 3, 1977: CASE STUDY

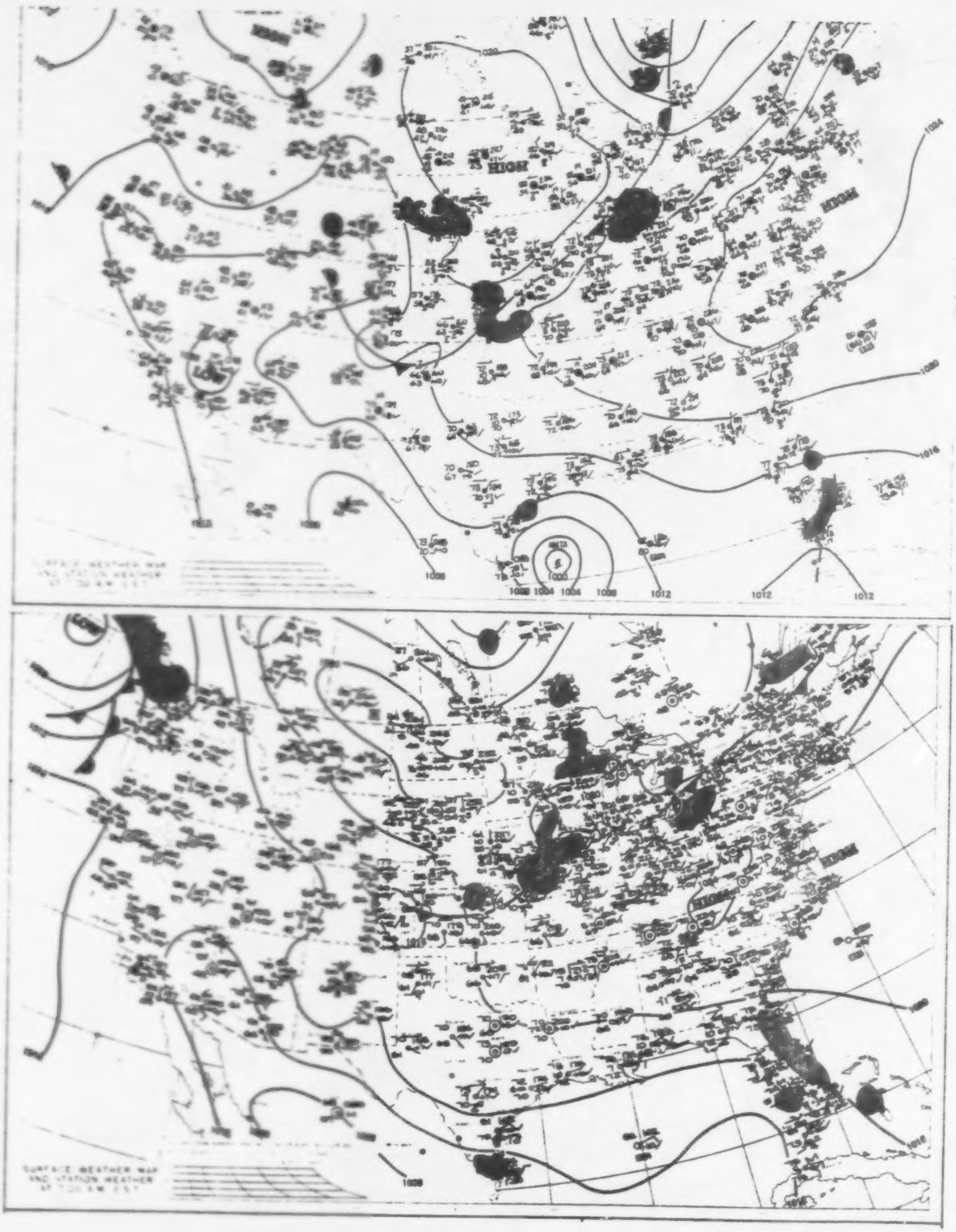
### 4.5.1 Introduction

The dates September 2 and 3 (a Friday and Saturday) were chosen for study because (1) the flow of air was consistently from the south on both days causing transport of urban air northward, (2) high concentrations of ozone (>0.08 ppm) were measured at several of the sites in the monitoring network, and (3) meteorological and pollutant measurements aloft were available.

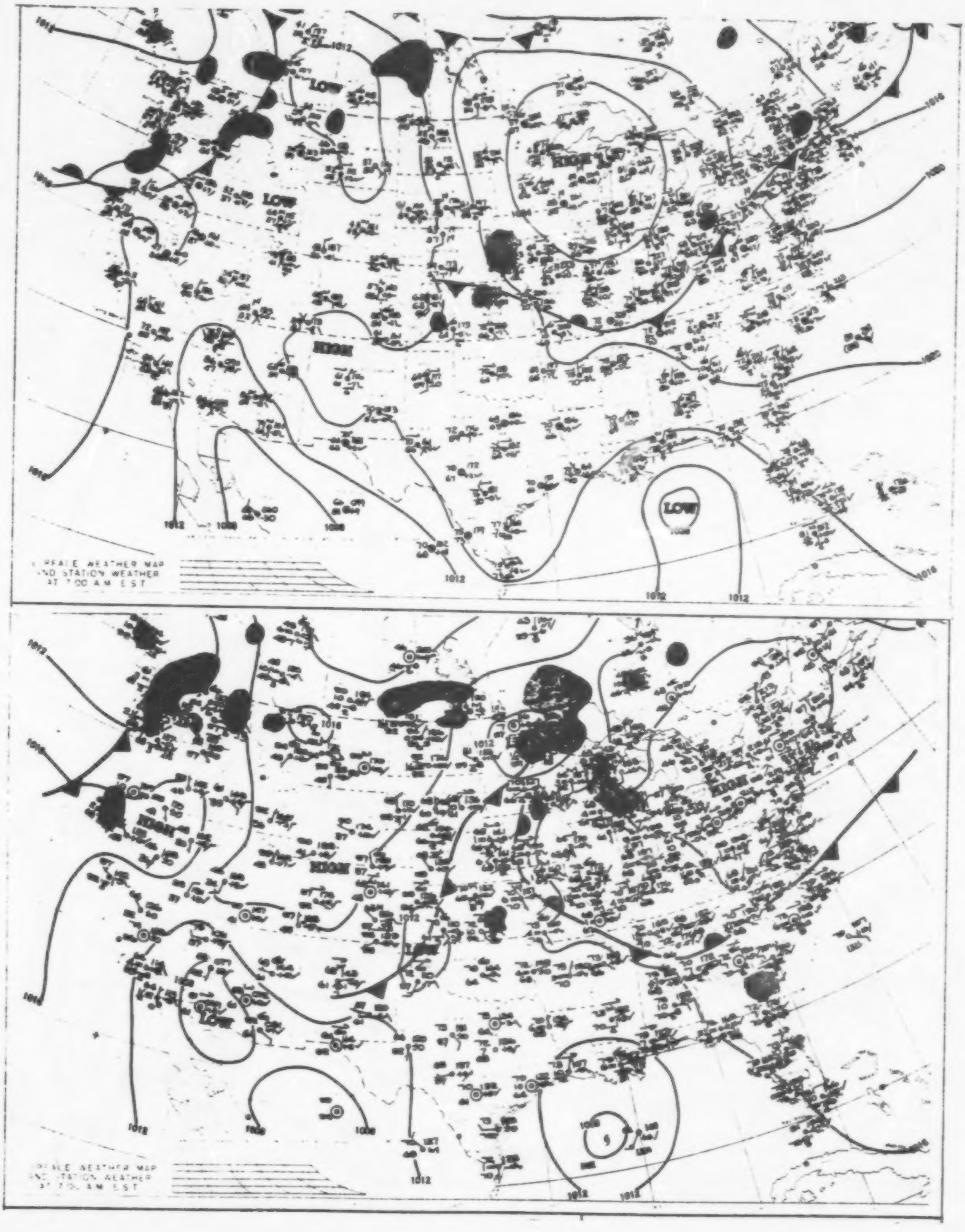
Figures and tables summarizing the meteorological and chemical data for this case study period are presented below. Figures 4.29a through 4.29d are the National Weather Service 0700 EST surface weather maps for the United States for September 1 through September 4. Figures 4.30 and 4.31 show the synoptic and local (mesoscale) backward air parcel trajectories for the case study days. Figures 4.32a and 4.32b show the forward trajectories of the urban air parcel at selected times on September 2 and 3, respectively. Figure 4.33 represents the diurnal variation of temperature for the two days, and Figure 4.34 shows the daily variation in incident solar radiation. Figure 4.35 illustrates the diurnal profiles for NO and $NO_2$ at the two city sites and Figure 4.36 illustrates the diurnal profiles for ozone for each site in the network.

Selected data from the aircraft flights are also presented. Figures 4.37 and 4.38 show the flight track for the morning and afternoon operations. Figure 4.39 shows the data from the morning spiral at Liberty Mounds on September 2. Ozone data taken during the horizontal traverses of the morning flight are plotted in Figure 4.40. The data collected during the vertical spiral above the central business district are shown in Figure 4.41. Data from the horizontal traverses on the afternoon flight for ozone are illustrated in Figure 4.42. Finally, the afternoon spiral data are shown in Figure 4.43. Similar depictions for the morning and afternoon flights of September 3 are presented in Figures 4.44 through 4.48.

Values for the individual hours of data for meteorological and chemical parameters are not reported here but can be found in Volume II of this report.


HIGH
LOW
HIGH
HIGH
LOW
1020
1024
1020
1016
1012
1012
1012
1008
1004
1004
1000
1008
1008
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.
LOW
HIGH
HIGH
1016
1008
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.

Figures 4.29a and 4.29b. United States surface weather maps for September 1 and September 2, 1977.


LOW
LOW
HIGH
HIGH
LOW
1012
1016
1008
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.
HIGH
HIGH
HIGH
LOW
1012
1016
1008
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.

Figures 4.29c and 4.29d. United States surface weather maps for September 3 and September 4, 1977.

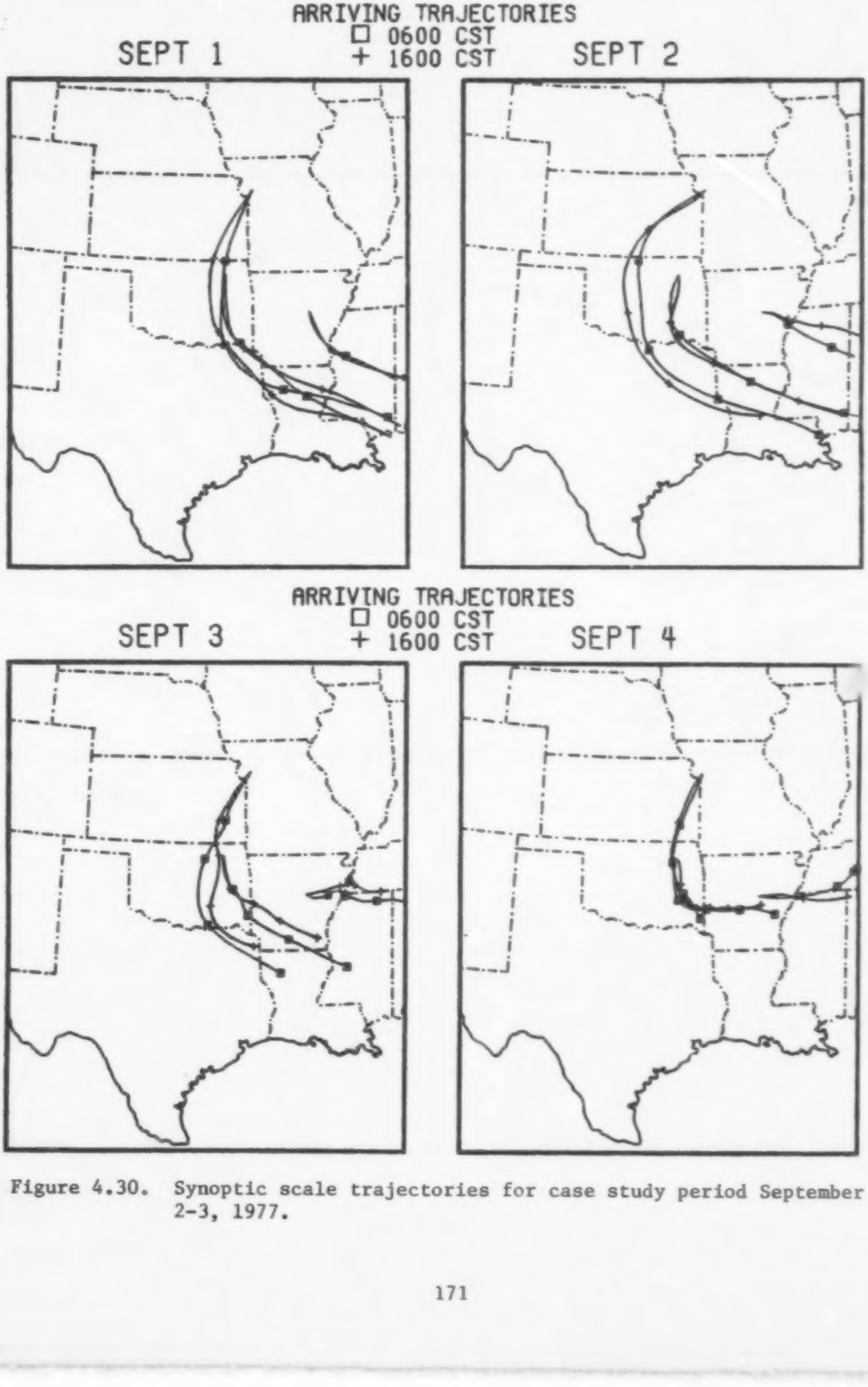

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
SEPT 1
SEPT 2
ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
SEPT 3
SEPT 4

Figure 4.30. Synoptic scale trajectories for case study period September 2-3, 1977.

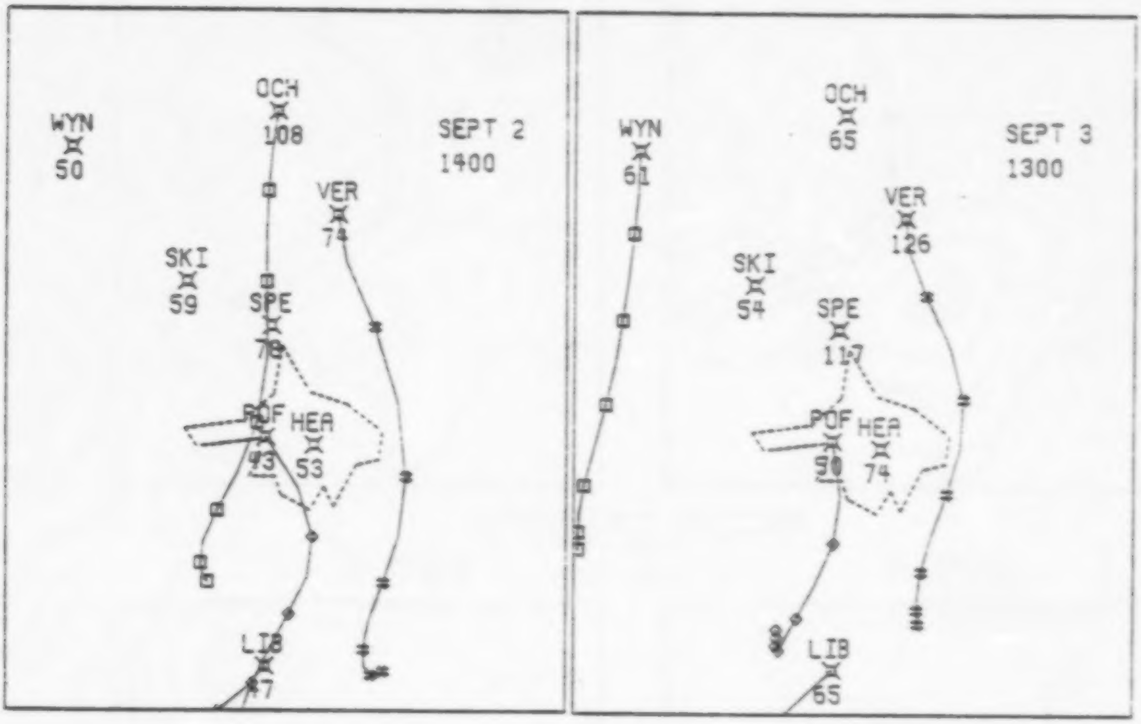

WYN
50
OCH
108
SEPT 2
1400
VER
74
SKI
59
SPE
78
POF
43
HEA
53
LIB
47
WYN
61
OCH
65
SEPT 3
1300
VER
126
SKI
54
SPE
117
POF
50
HEA
74
LIB
65

Figure 4.31. Mesoscale trajectories for case study period September 2-3, 1977.

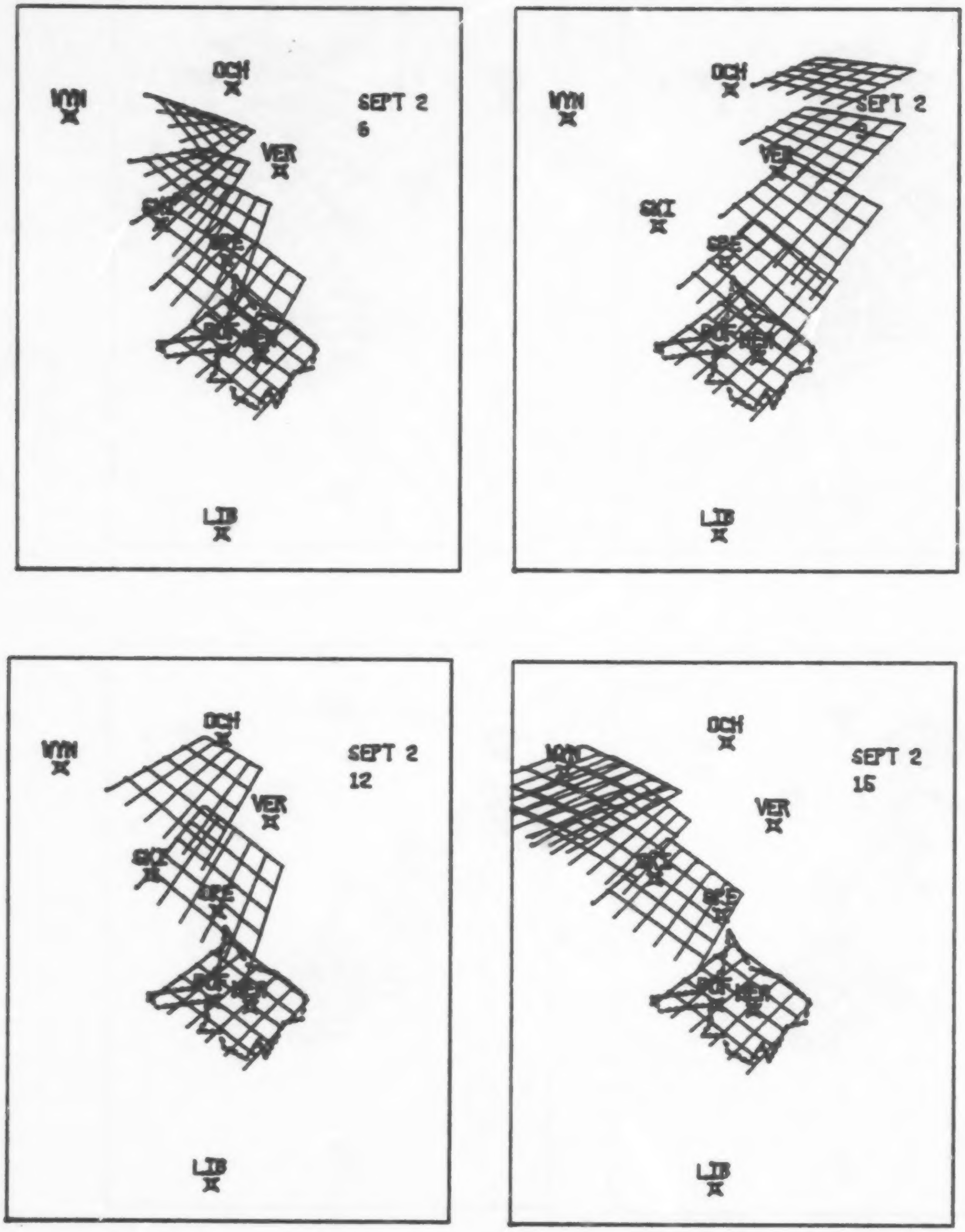

OCH
WYN
SEPT 2
6
VER
SKI
LIB
OCH
WYN
SEPT 2
VER
SKI
LIB
OCH
WYN
SEPT 2
12
VER
SKI
LIB
OCH
WYN
SEPT 2
15
VER
LIB

Figure 4.32a. Forward air parcel trajectories for September 2, 1977.

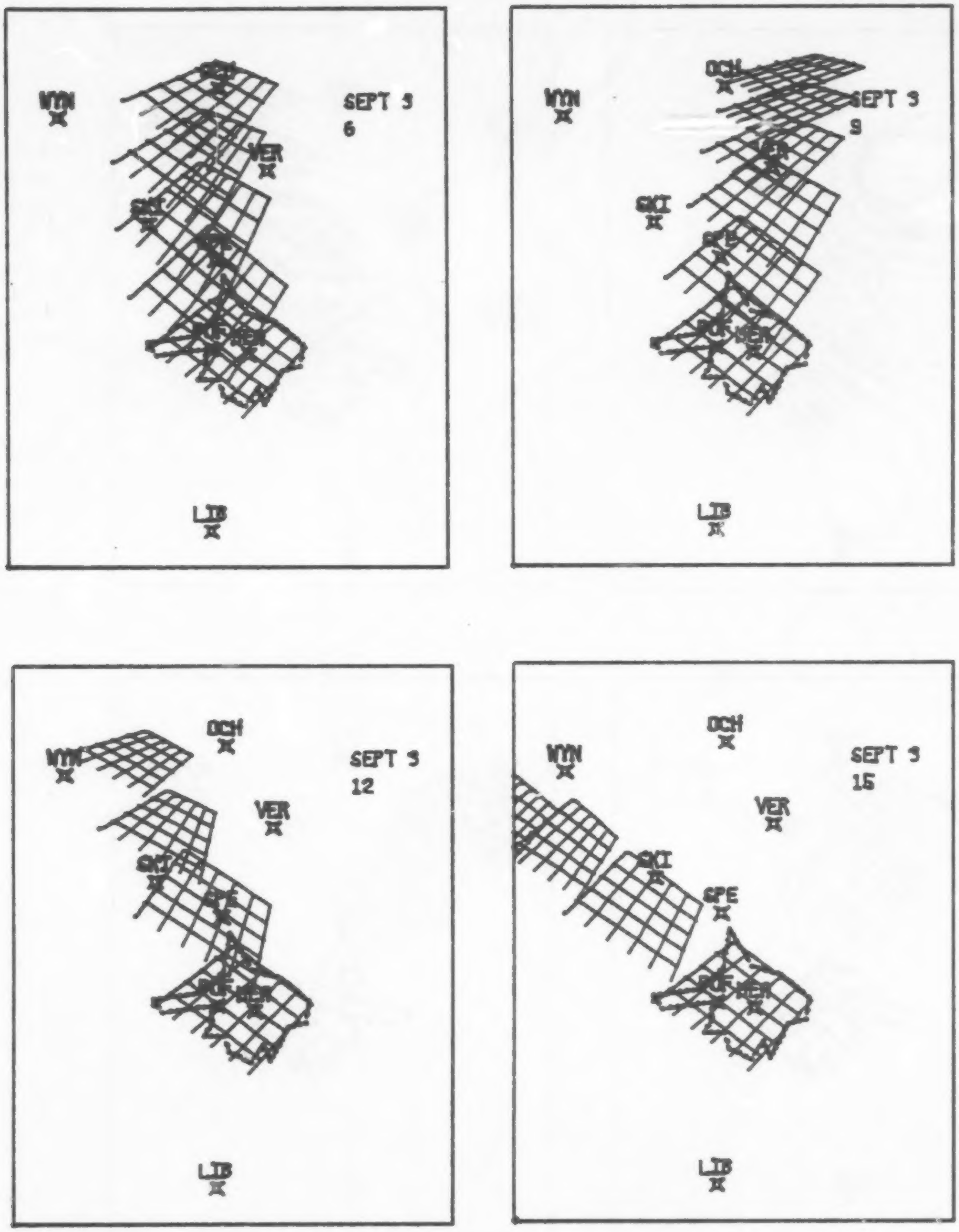

WYN
SEPT 3
6
VER
SKI
LIB
OCH
WYN
SEPT 3
9
SKI
SPE
LIB
OCH
WYN
SEPT 3
12
VER
SKI
SPE
LIB
OCH
WYN
SEPT 3
15
VER
SKI
SPE
LIB

Figure 4.32b. Forward air parcel trajectories for September 3, 1977.

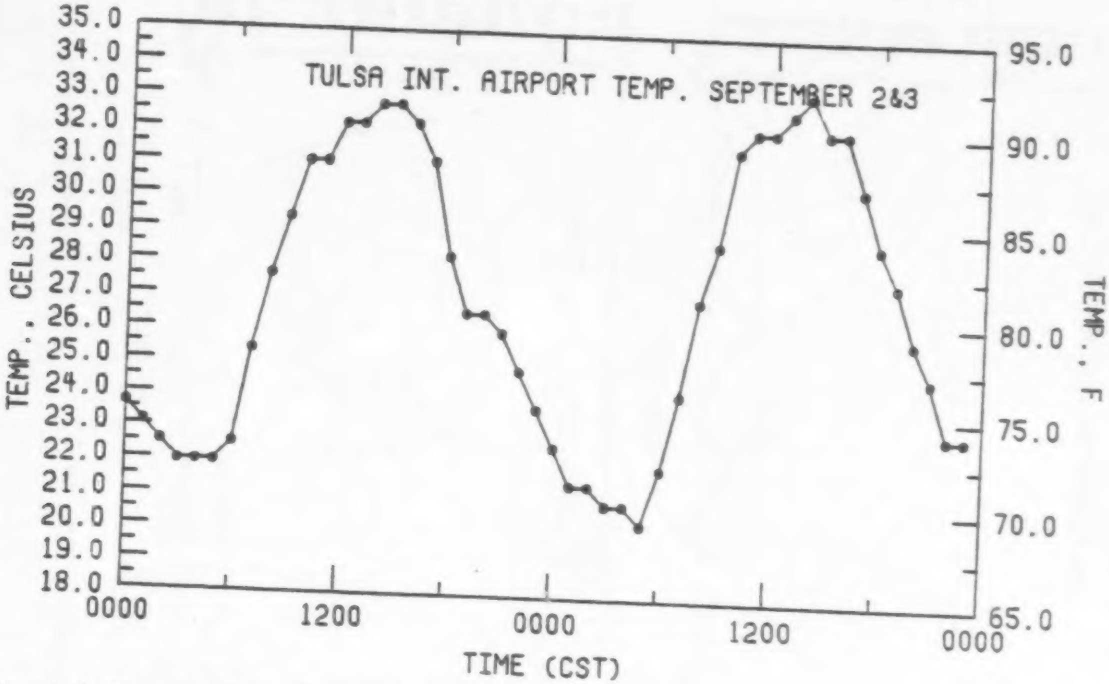


Figure 4.33. Diurnal variation of temperature for the period September 2-3, 1977.

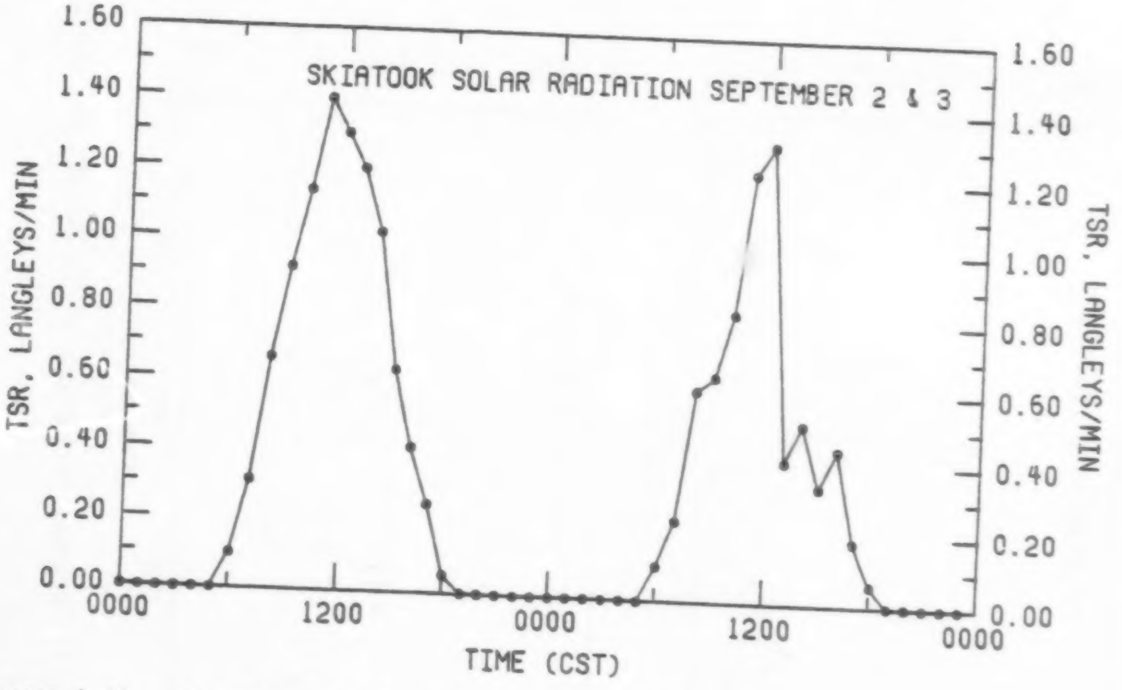


Figure 4.34. Diurnal variation of solar radiation for the period September 2-3, 1977.

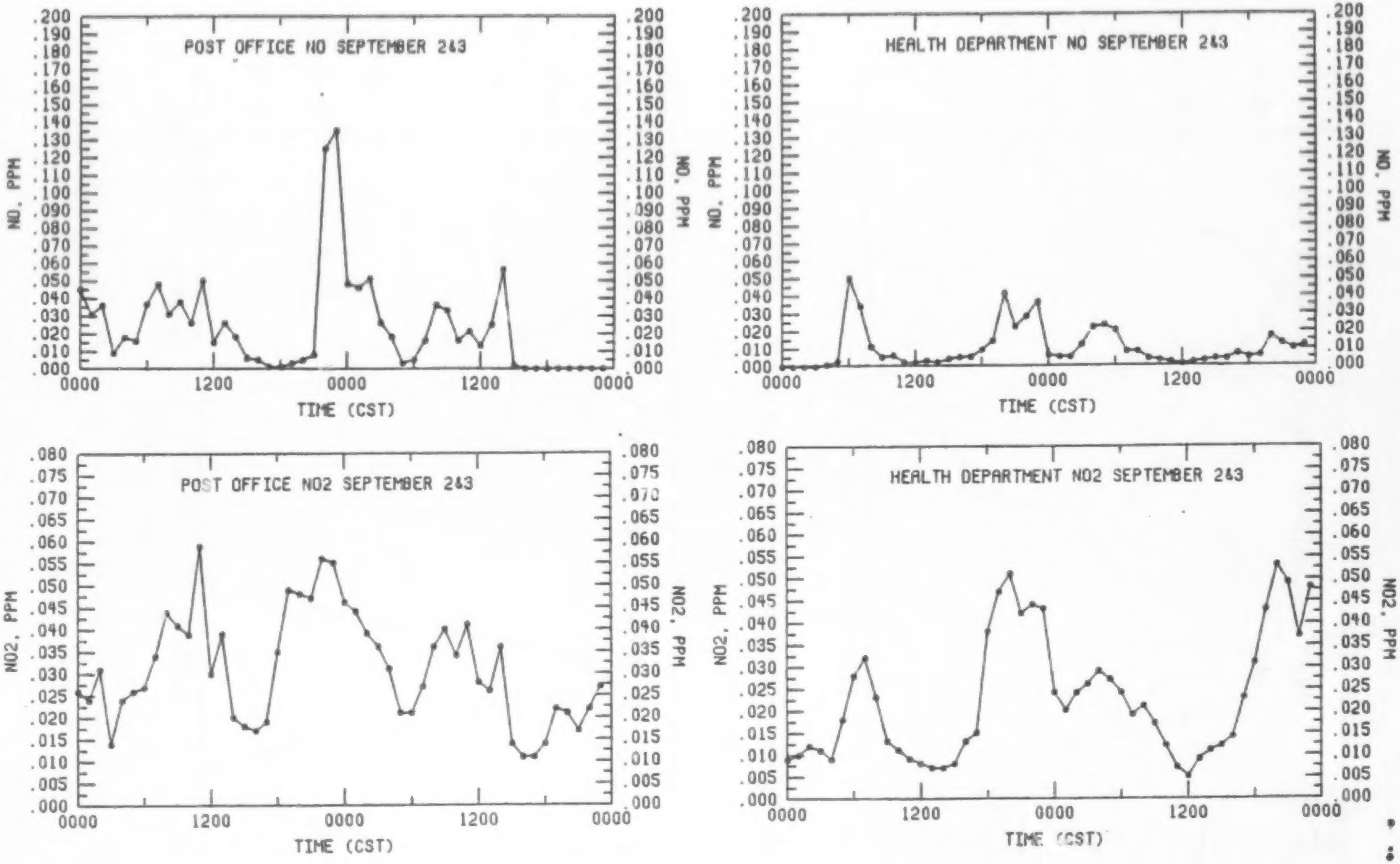


Figure 4.35. Diurnal variations of NO and $NO_2$ for the period September 2-3, 1977.

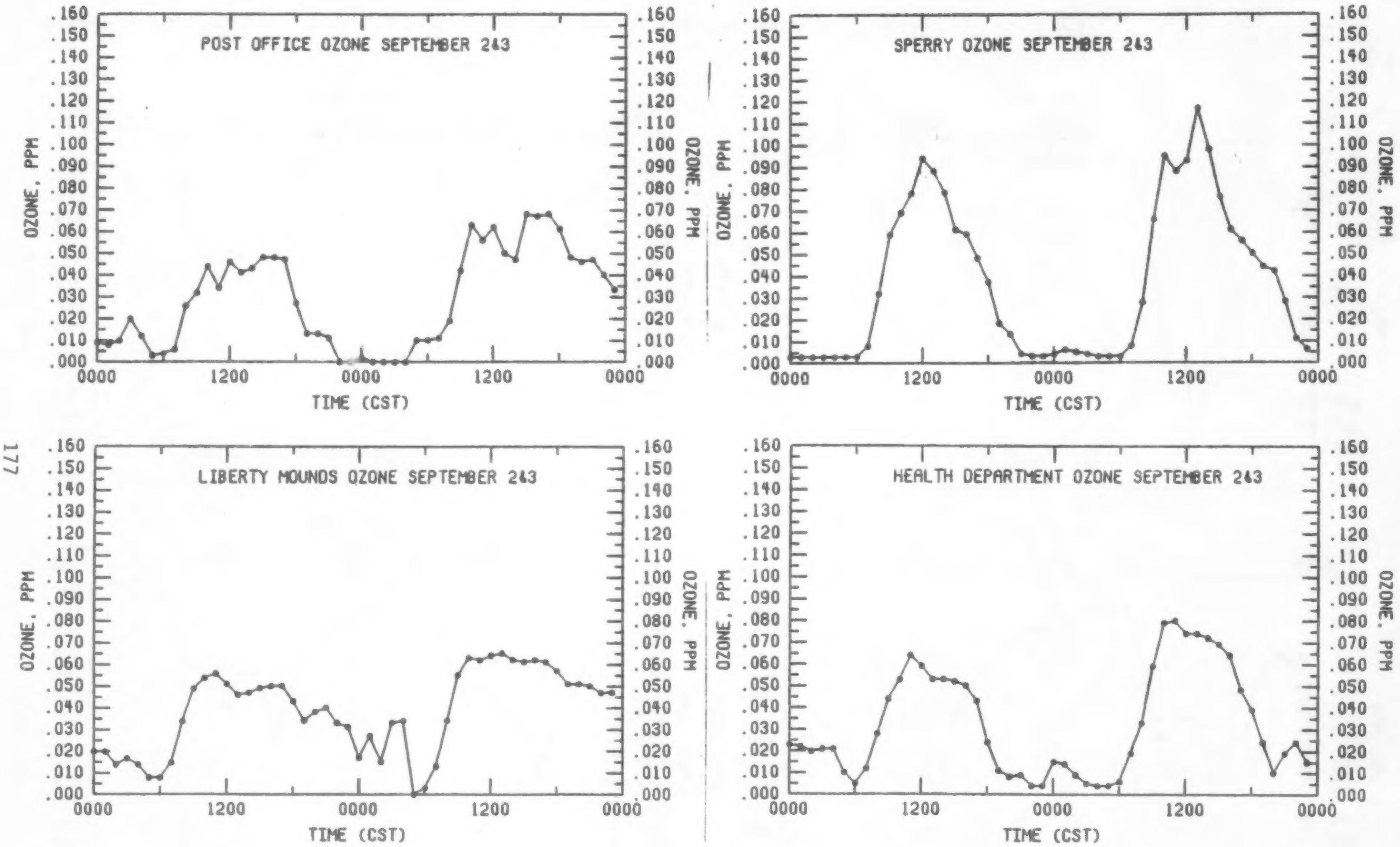


Figure 4.36. Diurnal variation of ozone for the period September 2-3, 1977.

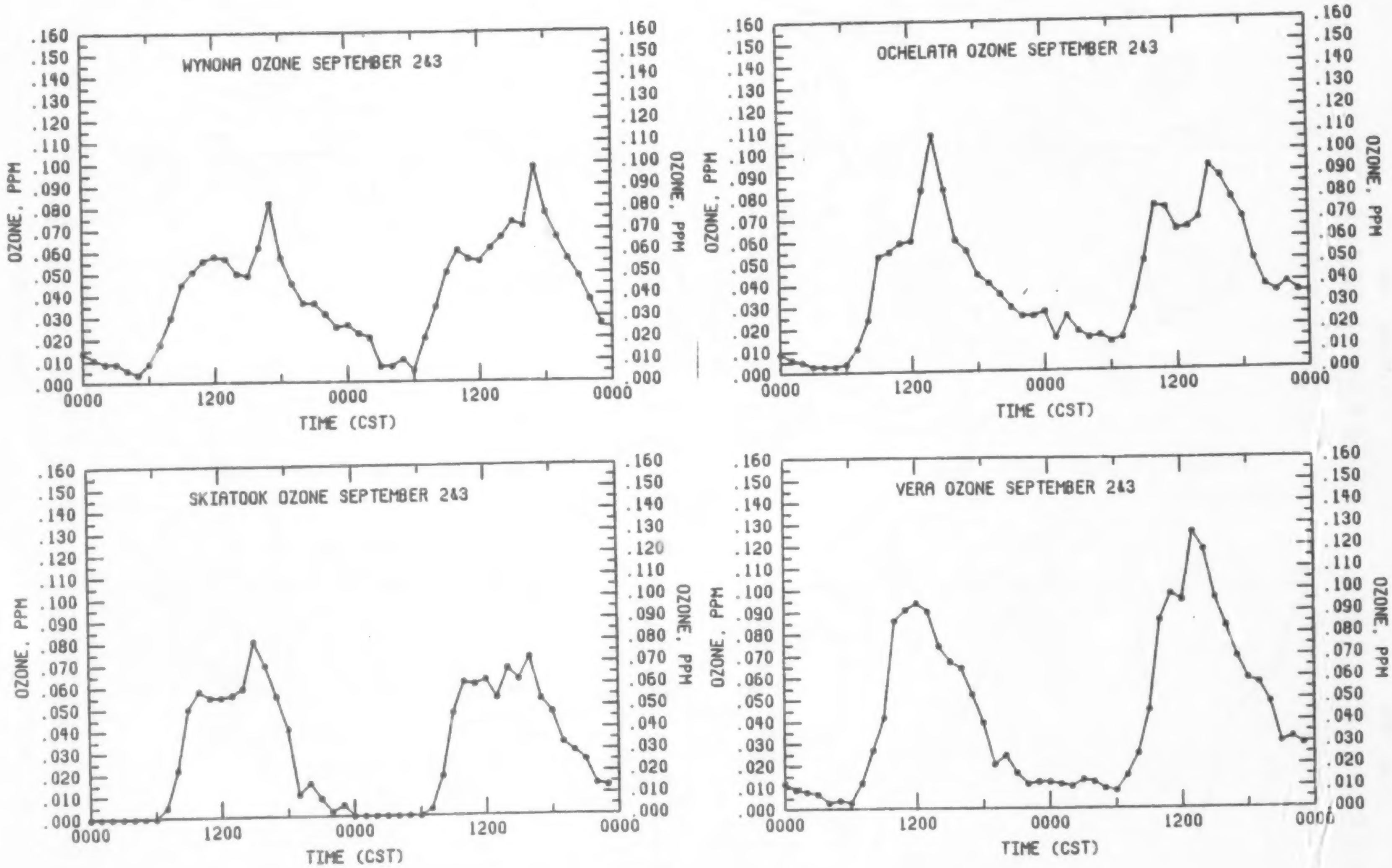


Figure 4.36. Diurnal variation of ozone for the period September 2-3, 1977. (continued).

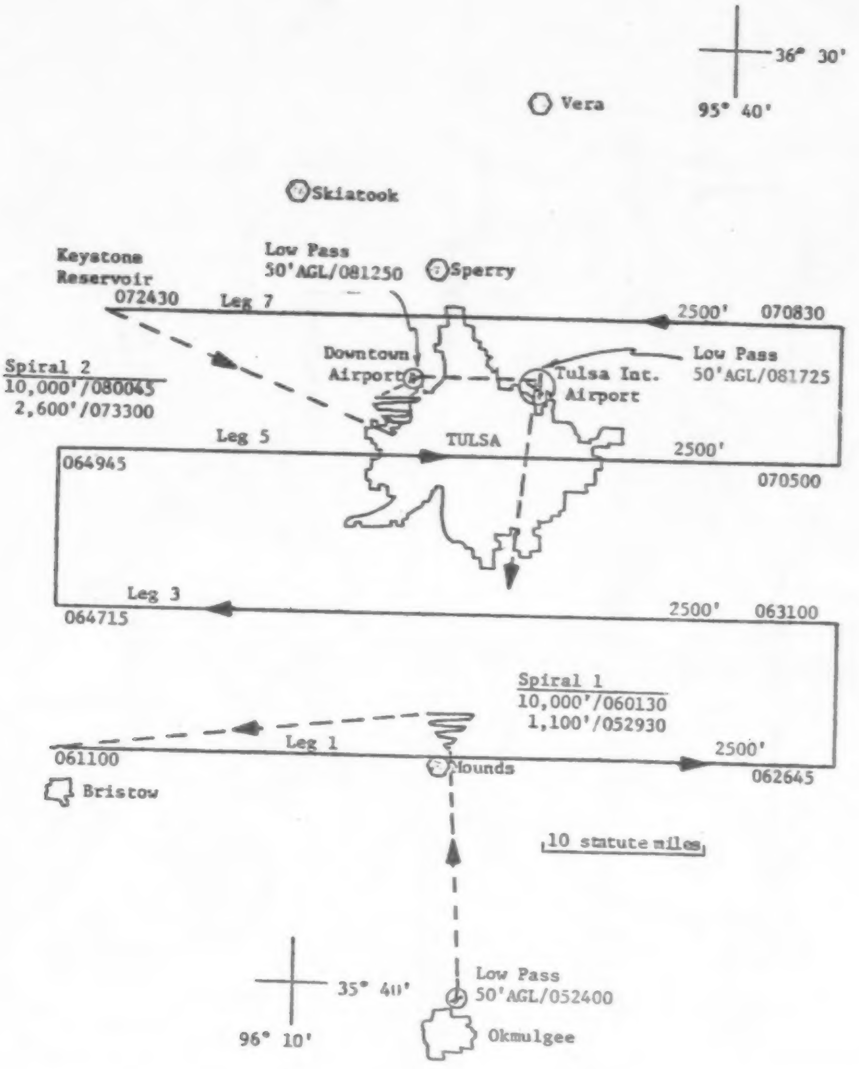
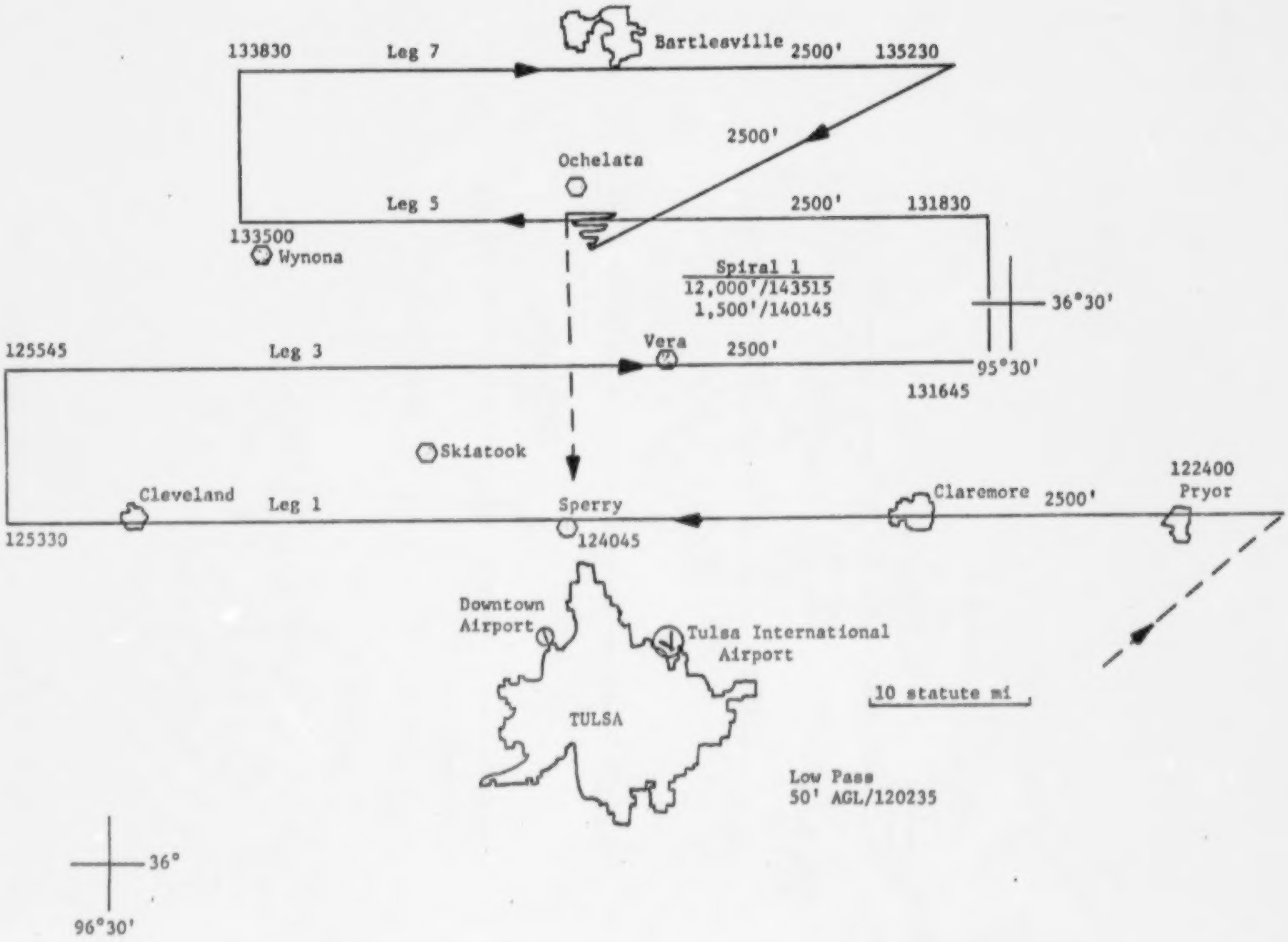

36° 30'
95° 40'
Vera
Skiatook
Keystone Reservoir
Low Pass 50'AGL/081250
Sperry
072430
Leg 7
2500'
070830
Spiral 2
10,000'/080045
2,600'/073300
Downtown Airport
Tulsa Int. Airport
Low Pass 50'AGL/081725
Leg 5
TULSA
2500'
064945
070500
Leg 3
2500'
063100
064715
Spiral 1
10,000'/060130
1,100'/052930
Leg 1
2500'
061100
062645
Mounds
Bristow
10 statute miles
35° 40'
96° 10'
Low Pass 50'AGL/052400
Okmulgee

Figure 4.37. Tulsa Flight T09, September 2, 1977. AM Transport Pattern.



133830
Leg 7
Bartlesville
2500'
135230
2500'
Ochelata
Leg 5
2500'
131830
133500
Wynona
Spiral 1
12,000'/143515
1,500'/140145
36°30'
125545
Leg 3
Vera
2500'
95°30'
131645
Skiatook
122400
Pryor
Cleveland
Leg 1
Sperry
Claremore
2500'
125330
124045
Downtown
Airport
Tulsa International
Airport
10 statute mi
TULSA
Low Pass
50' AGL/120235
36°
96°30'

Figure 4.38. Tulsa Flight T10, September 2, 1977. PM Transport Pattern.

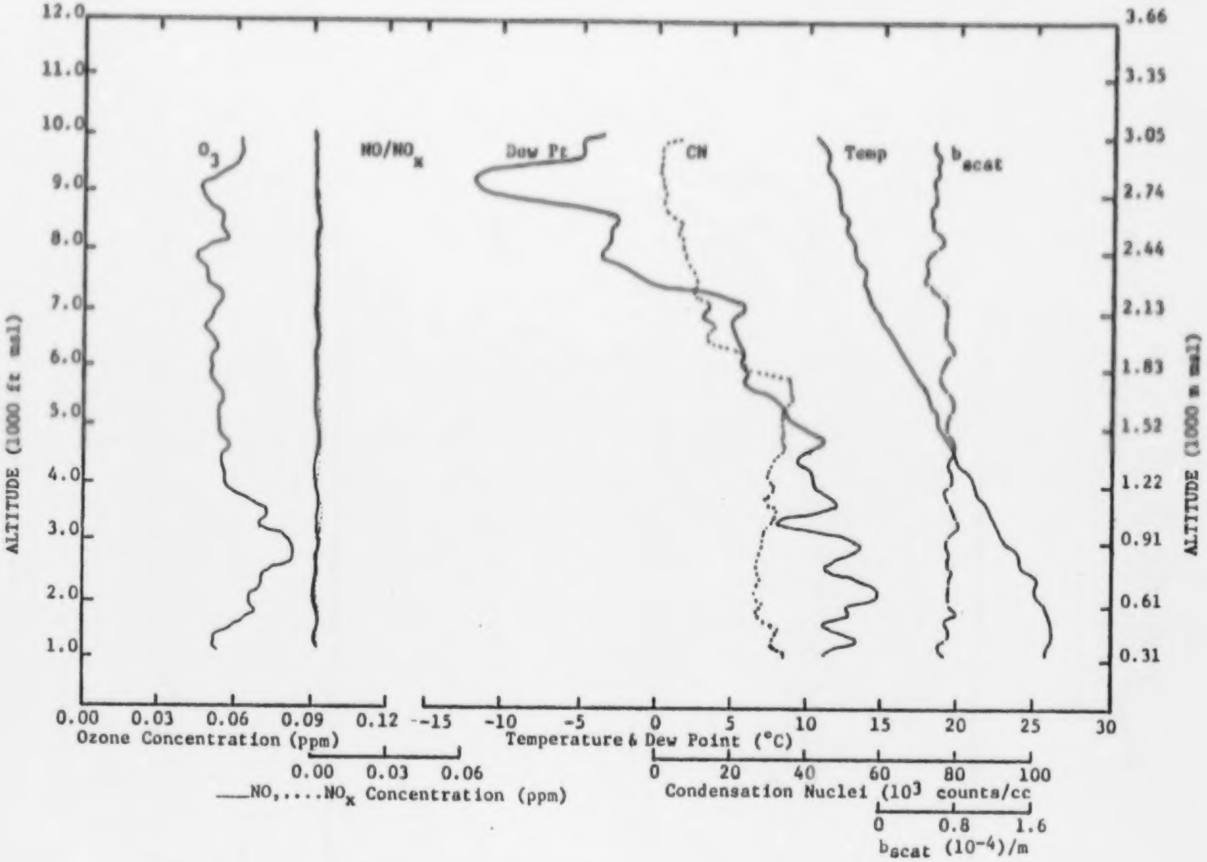


Figure 4.39. Tulsa Flight T09, September 2, 1977. Vertical Spiral, Liberty Mounds, 0529-0601 CST.

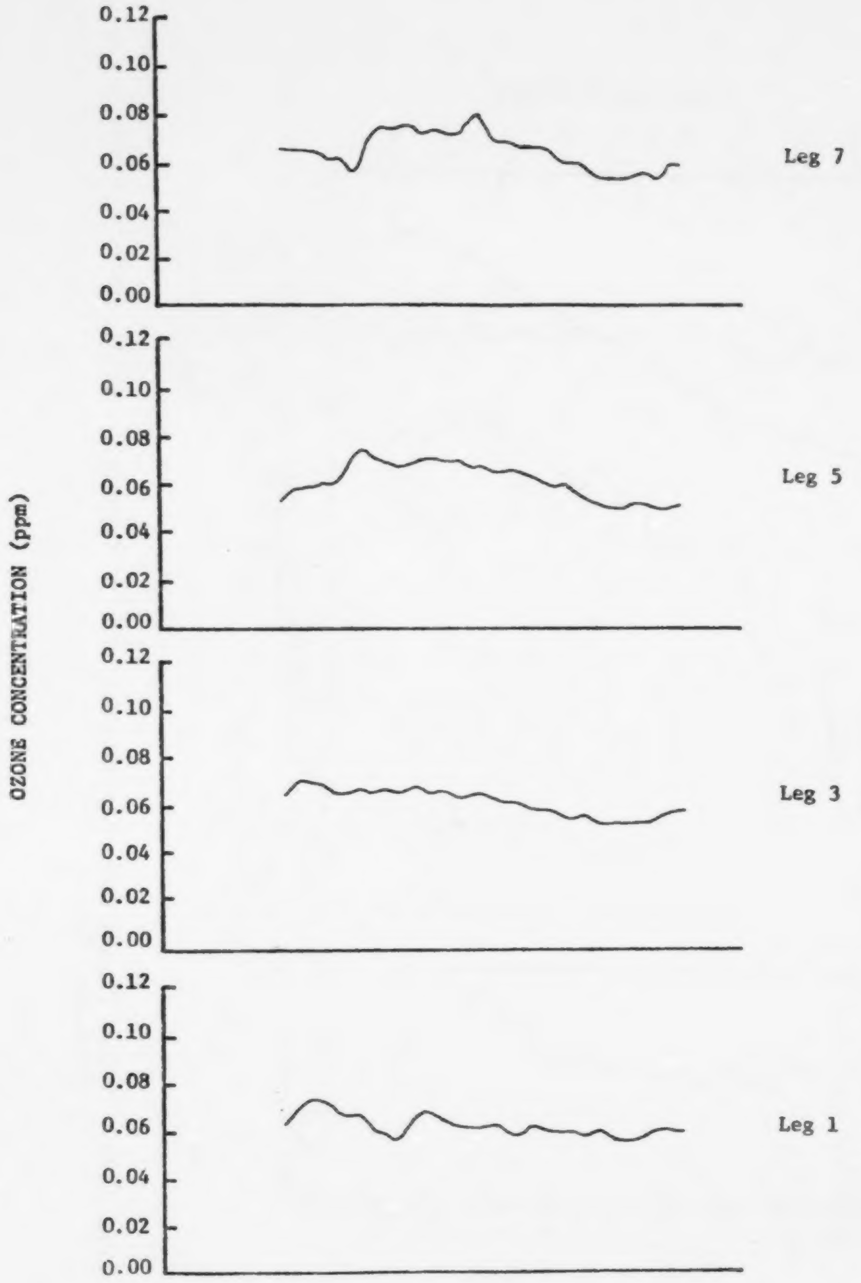


Figure 4.40. Tulsa Flight T09, September 2, 1977.
Horizontal Traverse, Ozone Concentration.

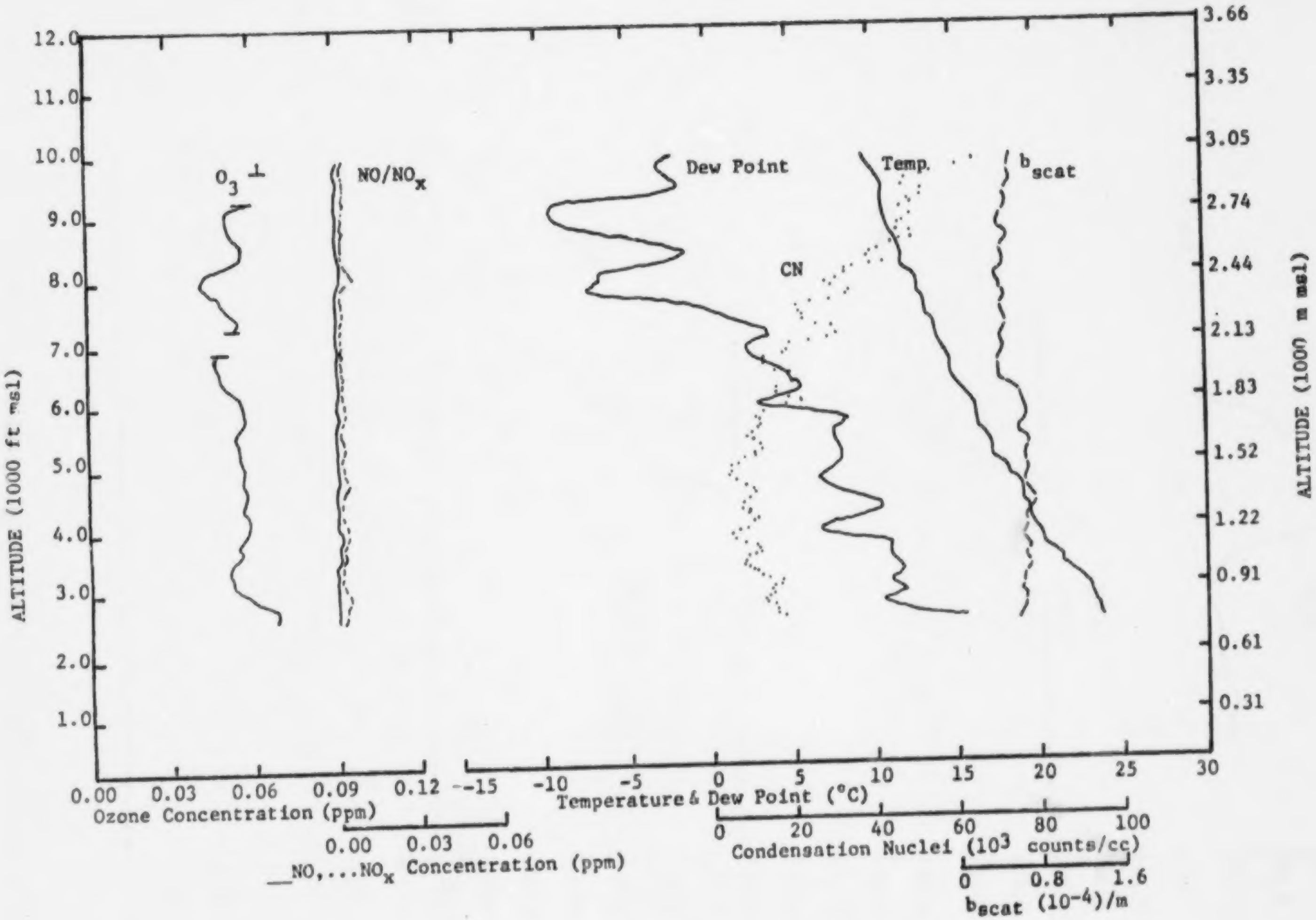


Figure 4.41. Tulsa Flight T09, September 2, 1977, Vertical Spiral, Central Business District, 0733-0800 CST.

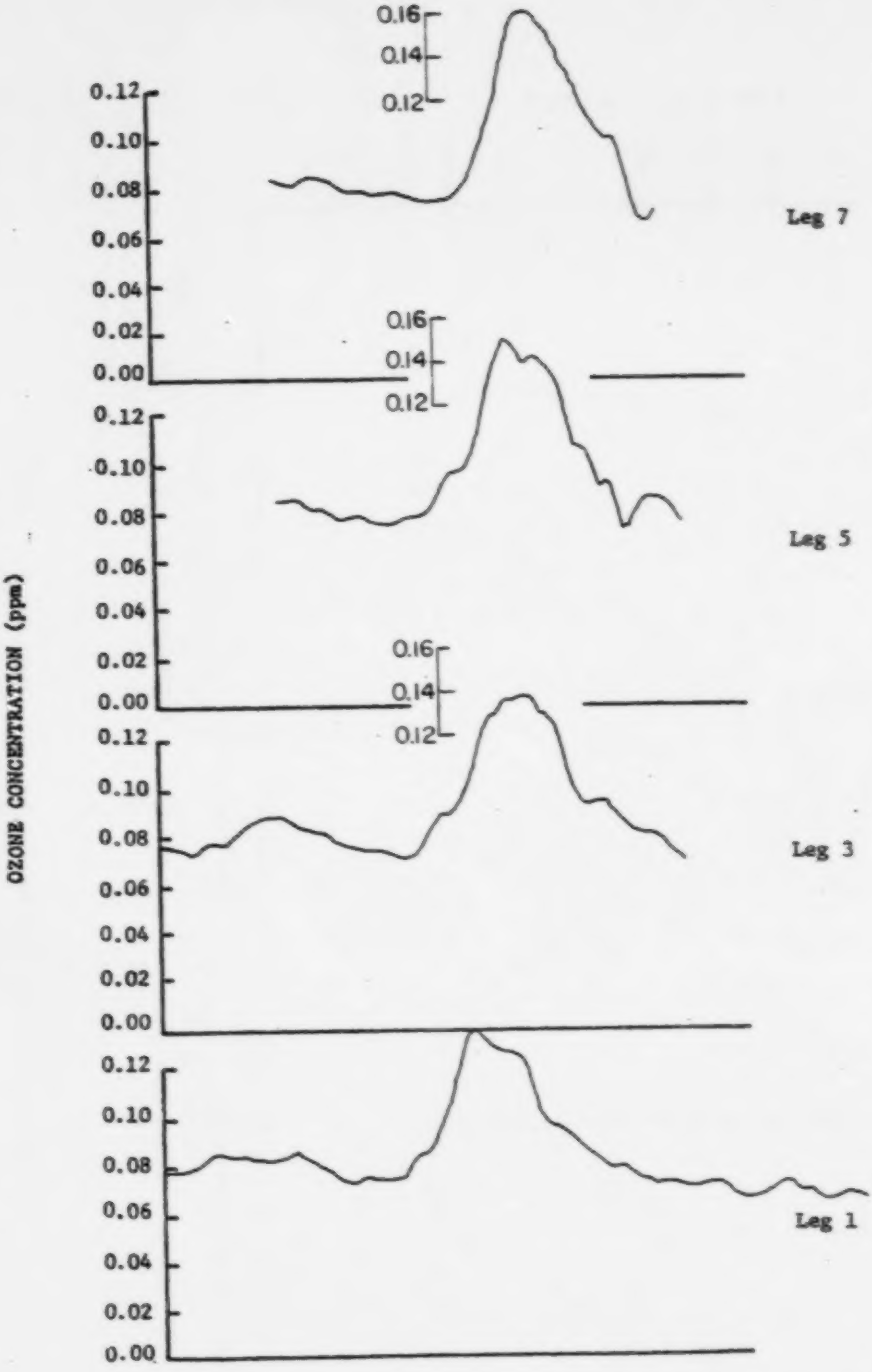


Figure 4.42. Tulsa Flight T10, September 2, 1977.
Horizontal Traverse, Ozone Concentration.

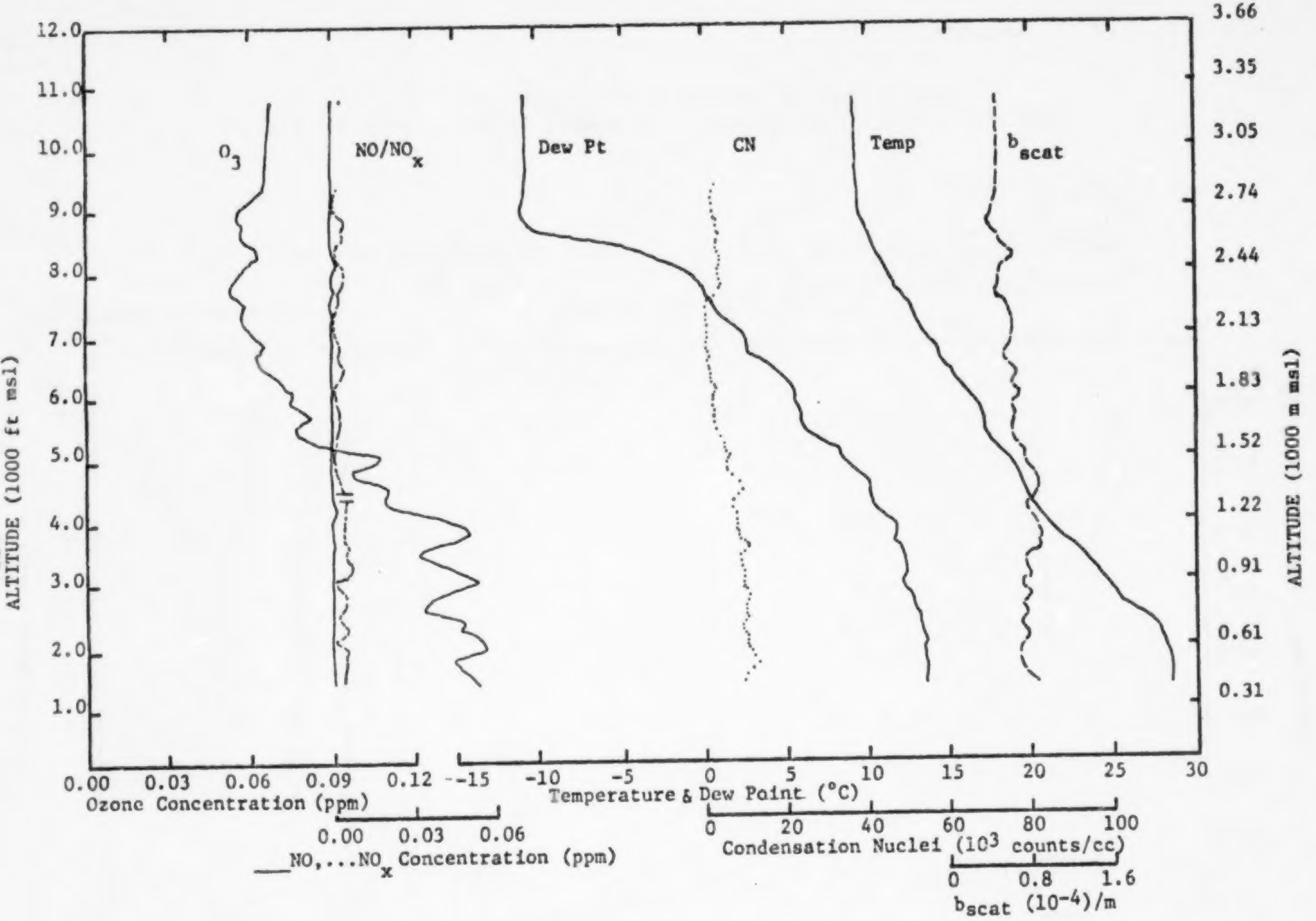


Figure 4.43. Tulsa Flight T10, September 2, 1977. Vertical Spiral, Ramona, 1401-1435 CST.

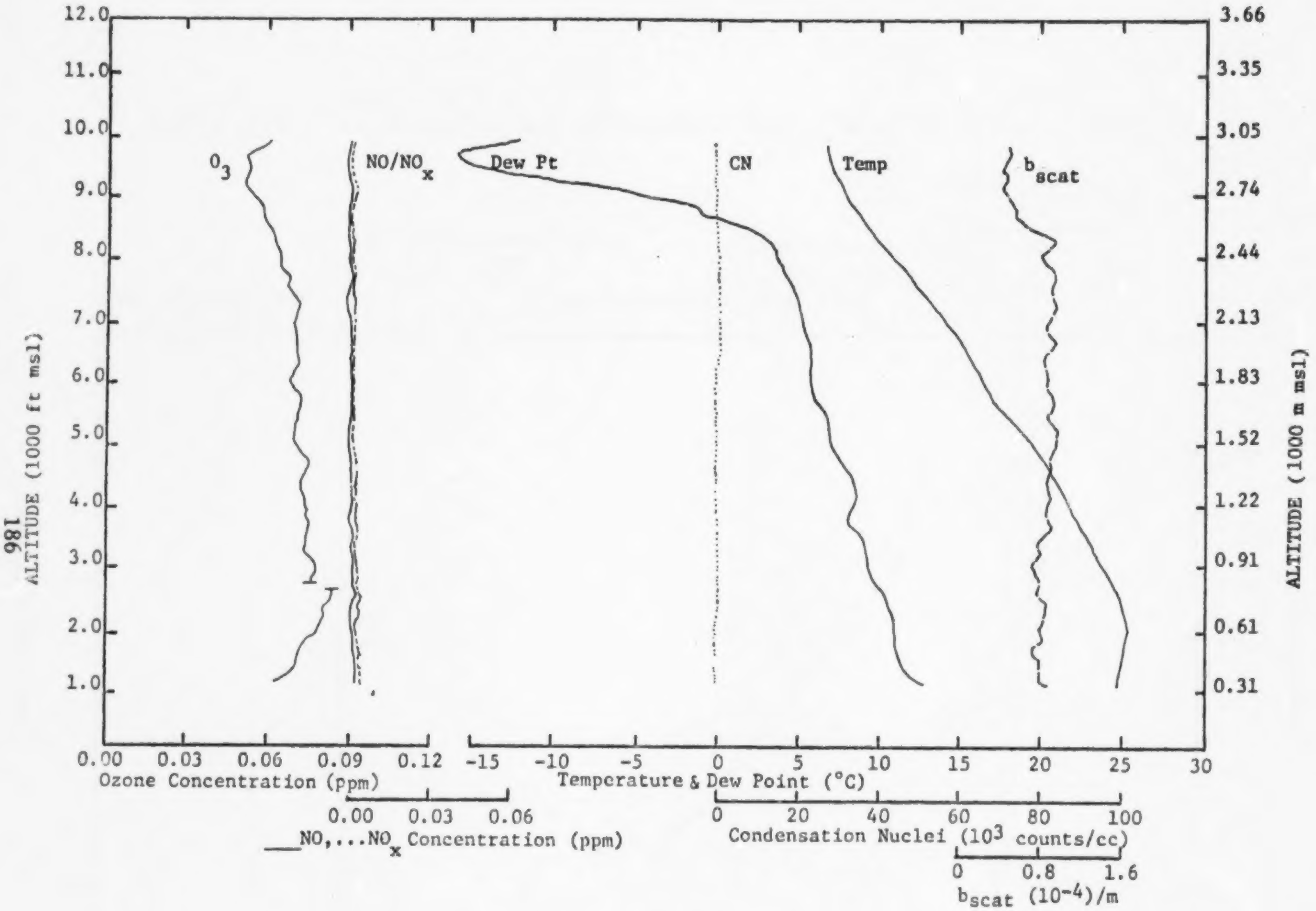


Figure 4.44. Tulsa Flight T11, September 3, 1977. Vertical Spiral, Liberty Mounds, 0526-0554 CST.

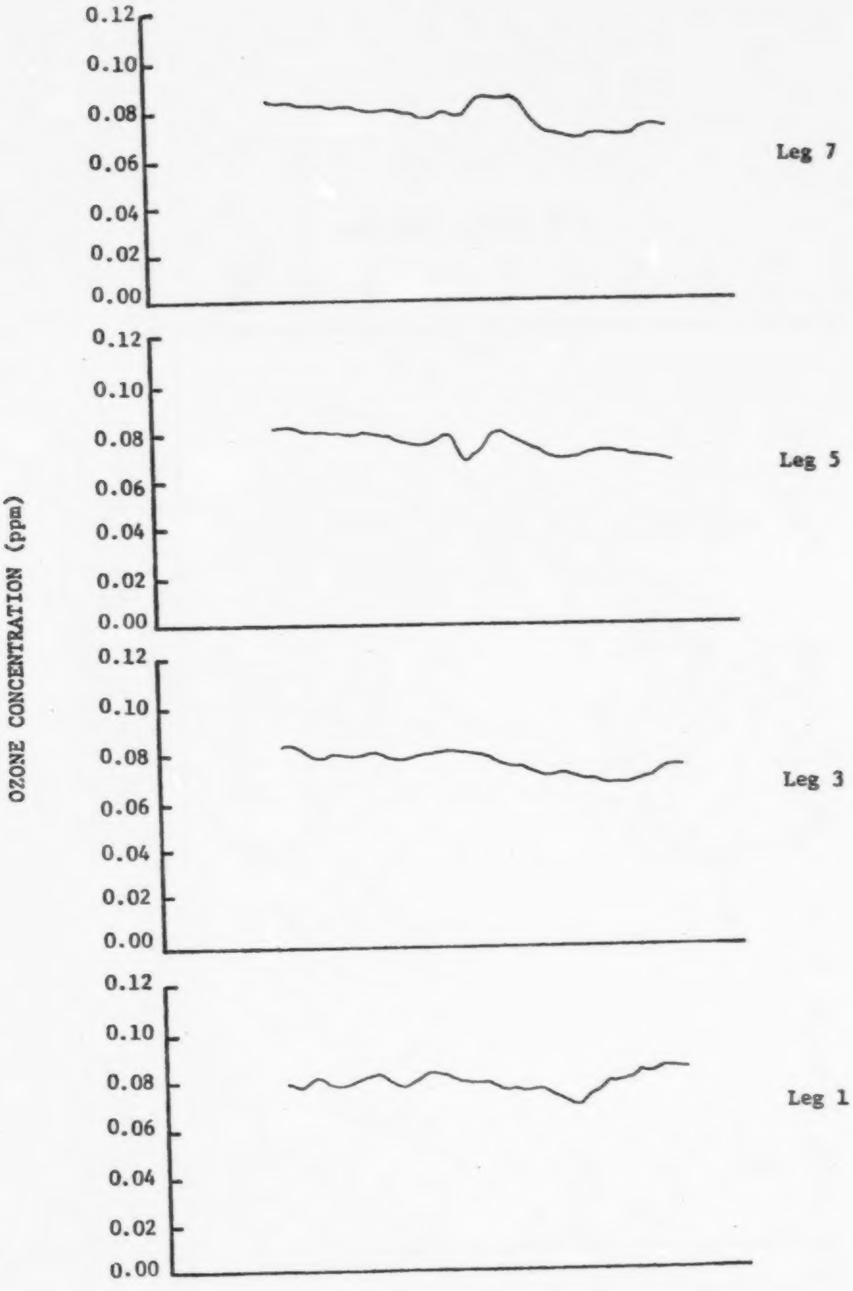


Figure 4.45. Tulsa Flight T11, September 3, 1977. Horizontal Traverse, Ozone Concentration. Concentration.

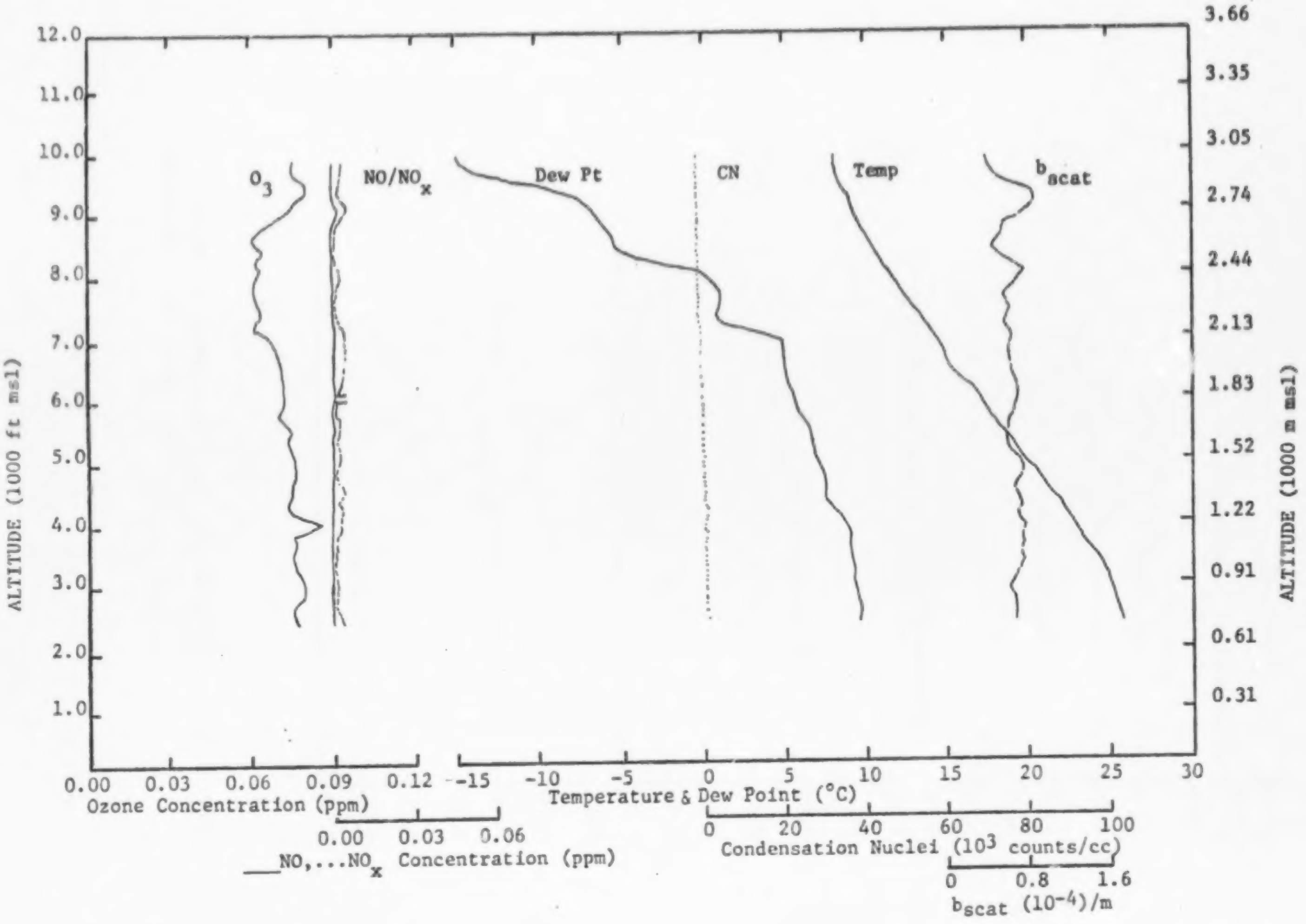


Figure 4.46. Tulsa Flight T11, September 3, 1977. Vertical Spiral, Central Business District, 0723-0746 CST.

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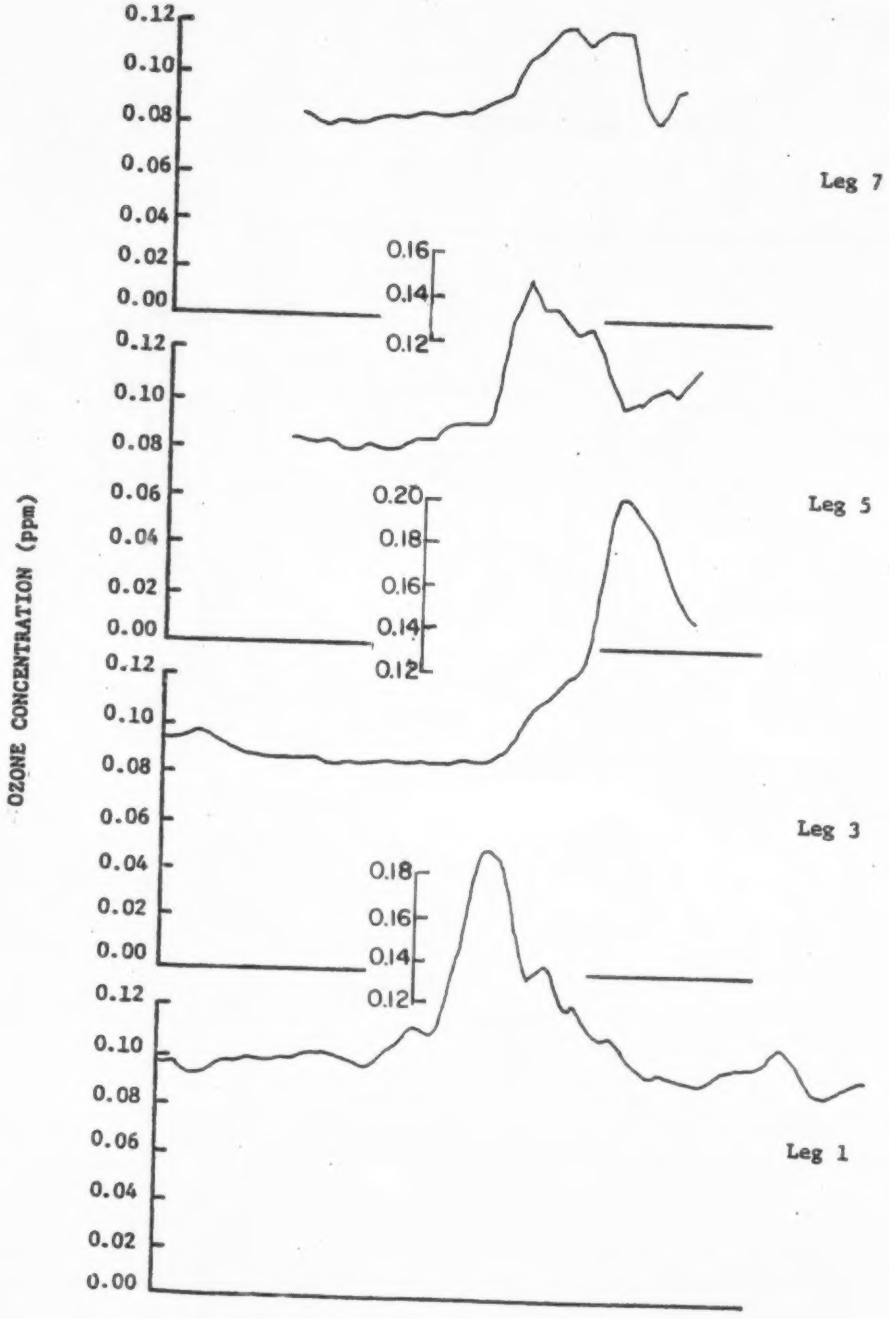

Figure 4.47. Tulsa Flight T12, September 3, 1977. Horizontal Traverse, Ozone Concentration.

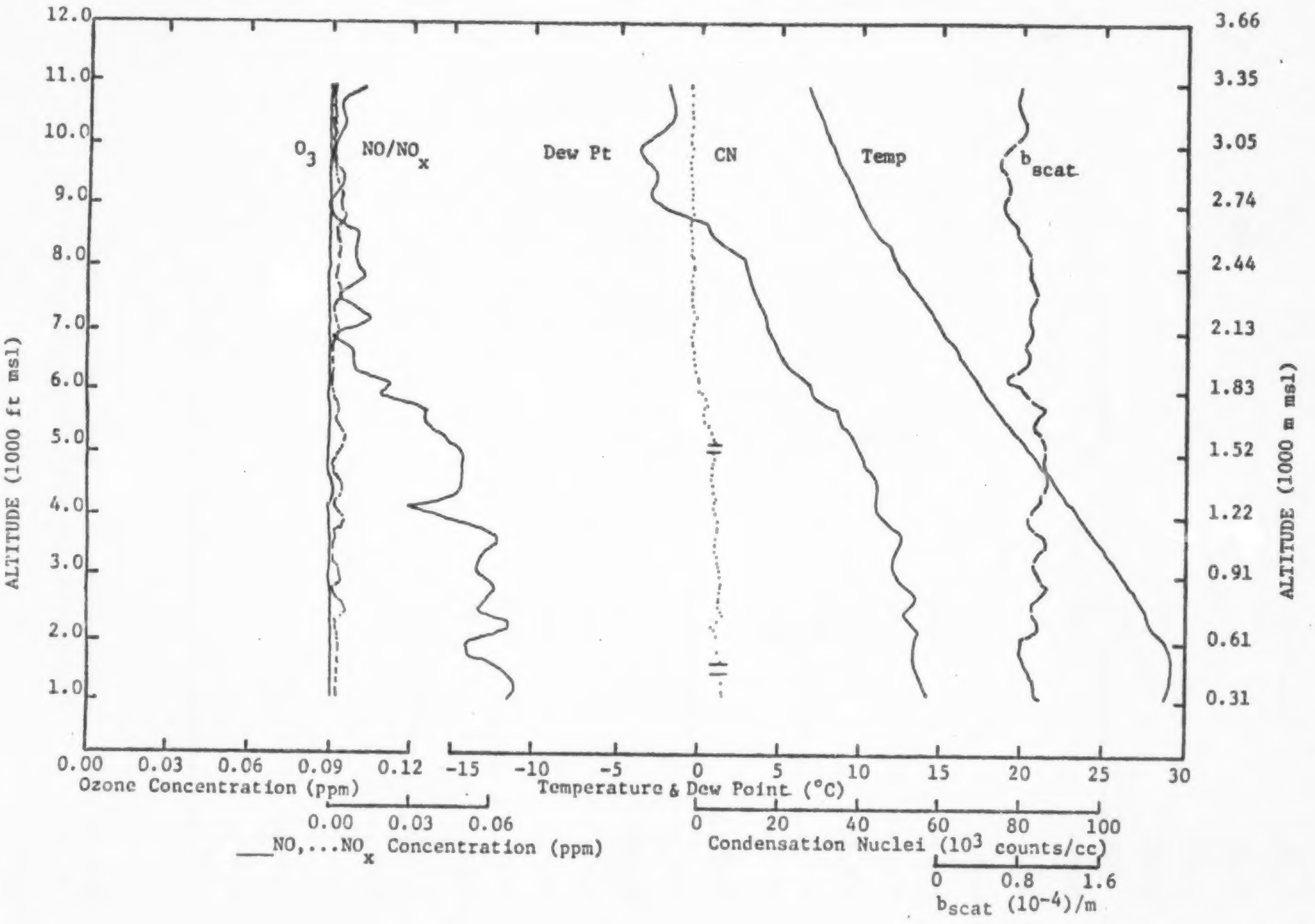

Figure 4.48. Tulsa Flight T12, September 3, 1977. Vertical Spiral, Ramona, 1408-1439 CST.

### 4.5.2 General Description of the Case Study

The major synoptic influence on the Tulsa area on September 2 was a high-pressure area that was centered over western Virginia (Figure 4.29). The synoptic trajectories for both arrival times on September 2 (Figure 4.30) show that there had been rapid transport from southern Alabama during the 48 hours preceding air parcel arrival in Tulsa. During the last 12 hours of both the 0600 and 1600 trajectories, air flow from due south was indicated. The local (mesoscale) back trajectories, shown in Figure 4.31, also show steady southerly winds to have been affecting the Tulsa area. The forward trajectories of the urban air parcel (Figure 4.32) also indicate transport of the urban air to the north until 1500 CST. The trajectory calculated for air leaving Tulsa at 1500 shows transport to the northwest. The solar radiation reached a maximum of approximately 1.4 langleys per minute at 1100 and, although the profile was not completely symmetric, there were no extensive periods of cloud cover indicated.

The 6-9 a.m. CDT average concentrations of selected hydrocarbons, oxides of nitrogen, and selected ratios at the Post Office, Health Department, and Liberty Mounds are listed in Table 4.5. The monthly means and standard deviations of the same parameters are listed in Table 4.1. On September 2 the sum of NMHC at all three stations was greater than the monthly means. The total $NO_x$ concentrations were also greater than the monthly means. At the Post Office the percentage of the total NMHC due to vehicular emissions was equal to the September mean, implying that contributions from automobile emissions and from industrial emissions were elevated during the morning. At the Health Department the percentage of NMHC due to vehicular emissions was 99 percent indicating that there was a large contribution to NMHC concentrations from vehicular emissions. The concentrations of $NO_x$ that were measured during the 3-hour 6-9 a.m. CDT averaging period were also higher than the averages at each of the three stations. This may also have resulted from increased $NO_x$ emissions from vehicular sources.

On the 0700 EST surface weather map for September 3 (Figure 4.29), a frontal system that had been approaching Oklahoma as a cold front stalled in mid-Kansas. Although the high-pressure center weakened, it was still the major synoptic influence on Tulsa on September 3. The synoptic-scale trajec-

TABLE 4.5. 0500 TO 0800 CST AVERAGE CONCENTRATIONS OF SELECTED HYDROCARBONS AND OXIDES OF NITROGEN, AND DISTRIBUTIONS FOR SEPTEMBER 2 AND 3, 1977

| | ΣNMHC ppmC | NMHC Beckman ppmC | ΣAlkenes ppbC | Acetylene ppbC | n-Butane ppbC | % tailpipe emissions | NO ppm | $NO_2$ ppm | $NO_x$ ppm | $\frac{\Sigma NMHC}{NO_x}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Post Office | | | | | | | | | | |
| September 2 | 0.640 | -- | 79.8 | 30.0 | 60.4 | 73 | 0.034 | 0.029 | 0.063 | 10.16 |
| September 3 | 0.367 | -- | 51.0 | 2.0 | 40.0 | 51 | 0.008 | 0.023 | 0.031 | 11.84 |
| Health Dept. | | | | | | | | | | |
| September 2 | 0.398 | 0.42 | 17.4 | 25.0 | 40.4 | 99 | 0.029 | 0.026 | 0.055 | 7.14 |
| September 3 | 0.285 | 0.32 | 25.1 | 11.0 | 26.4 | 60 | 0.017 | 0.023 | 0.040 | 7.12 |
| Liberty Mounds | | | | | | | | | | |
| September 2 | 0.303 | -- | 3.5 | 1.0 | 36.0 | 5 | 0.003 | 0.007 | 0.010 | 30.29 |
| September 3 | 0.619 | -- | 5.7 | 2.0 | 63.6 | 5 | 0.007 | 0.011 | 0.018 | 34.42 |

tories for September 3 (Figure 4.30) indicate very similar motion to that of September 2, for both arrival times. The wind speeds, however, are considerably less on the September 3 trajectories than on the September 2 trajectories. The local trajectories (Figure 4.31) are also nearly the same as those of September 2 and indicate steady northward transport until 1300. The forward trajectories of the urban air parcel (Figure 4.32) show slow northward transport of the urban air leaving Tulsa at 0600 and 0900 CST. The forward trajectories for departure times of 1200 and 1500, however, show slow transport of the urban air to the northwest. The solar radiation measured at Skiatook on September 3 showed a sharp decrease in solar radiation after 1200 CST.

The concentrations of NMHC measured at the Post Office and Health Department during the 6-9 a.m. CDT averaging period were considerably less on September 3, a Saturday, than they were on September 2 (Table 4.5). In addition, the percentage of the total NMHC due to vehicular emissions also decreased considerably on September 3 as did the 3-hour $NO_x$ average concentrations. At Liberty Mounds, however, there was 0.619 ppmC of NMHC measured during the 6-9 a.m. CDT period, which was nearly three times the September mean. The percentage of that NMHC concentration due to vehicular emissions was 5 percent, the same as on September 2, and considerably lower than the September mean of 20 percent. The $NO_x$ concentrations measured during that 3-hour period were also increased over those measured on September 2 and were nearly four times the September mean. The increases in NMHC and $NO_x$ on September 3 at Liberty Mounds are assumed to have been caused by some industrial source.

On both September 2 and 3, aircraft measurements of $O_3$, $NO/NO_x$, CN, $b_{scat}$, temperature, and dewpoint were made upwind of Tulsa in the morning and downwind of Tulsa during the afternoon. These data describe the horizontal distribution at approximately 2,500 ft MSL and the vertical profiles at selected locations of the parameters measured. A complete description of the aircraft flight protocol and measurement system is given in Volume I of this report.

The flight tracks followed on the morning and afternoon flights on both September 2 and 3 are shown in Figures 4.37 and 4.38. On both days a stable layer was observed near the surface during the Liberty Mounds spiral that extended up to an altitude of 2,000 ft MSL. A 1,000- or 2,000-ft thick layer that had high ozone concentrations relative to the rest of the spiral ozone data was observed on both days immediately above the stable surface layer. On September 2 the maximum ozone concentration of approximately 0.080 ppm was measured in the high ozone layer at approximately 2,000 ft MSL (Figure 4.39). The background ozone concentration, which was assumed to be the average ozone concentration above the layer of high ozone, was approximately 0.05 ppm. A background ozone concentration of approximately 0.065 ppm was measured on each horizontal traverse of the morning flight (Figure 4.40) at 2,500 ft MSL. Another vertical spiral flown at the end of the flight over the central business district of Tulsa measured a background ozone concentration above 3,000 ft MSL that was very similar to that measured at Liberty Mounds. Although 2,600 ft was the lowest altitude at which measurements were made on the second spiral, the layer of ozone was also apparent (Figure 4.41).

The ozone data from the horizontal traverses on the afternoon flight clearly show an ozone plume extending to the north of Tulsa (Figure 4.42). The maximum ozone concentration of 0.156 ppm was measured on the last horizontal traverse approximately 40 miles downwind of Tulsa. The approximate average ozone concentration outside of the plume area was 0.08 ppm. The data from a vertical spiral flown near the center of the plume (Figure 4.43) clearly show that ozone concentrations in the lowest 5,000 ft MSL were greater than those measured on the remainder of the spiral.

On the vertical spiral over Liberty Mounds on September 3, the maximum ozone concentration was approximately 0.08 ppm at approximately 2,800 ft MSL (Figure 4.44). The average background ozone concentration above the high ozone layer was 0.07 ppm, which made the ozone layer less evident than that measured on September 2. The average background ozone concentration measured on the horizontal traverses of the morning flight was 0.08 (Figure 4.45), which was also increased over that measured on September 2. The vertical profile of ozone measured over the central business district on September 3 (Figure 4.46) shows a background of approximately 0.075 ppm. The ozone data from the horizontal traverses of the afternoon flight on September 3 (Figure

4.47) clearly show an ozone plume similar to the ozone plume measured on September 2. The maximum ozone concentration measured in the plume of 0.207 ppm occurred on the second horizontal traverse approximately 20 miles downwind of Tulsa. A vertical spiral was flown near the center of the plume on September 3 and, as on September 2, the ozone data indicate that the surface was the source of the plume ozone (Figure 4.48).

### 4.5.3 Analysis of September 2, 1977

High pressure centered over the mountainous areas of North Carolina, Virginia, and West Virginia controlled the weather in Oklahoma on September 2. The 0700 EST surface weather map for September 2 (Figure 4.29b) shows that there was a strong cold front approaching Oklahoma from the northwest. However, this cold front was prevented from moving through Oklahoma by the high-pressure system. The front stalled through the center of Kansas and never affected the Tulsa area. The influence of the high-pressure area resulted in steady winds through Oklahoma from the south and southeast. The wind flow brought warm moist air into the Tulsa area, and the lack of any other influences kept the skies mostly clear. Clouds that did develop over Tulsa on September 2 were mostly high-altitude cirrus clouds.

The synoptic trajectories for September 2 (Figure 4.30) clearly show the anticyclonic motion produced by the high pressure. The trajectories imply that air arriving in Tulsa had originated in the southern areas of Mississippi and Alabama approximately 36 hours earlier. The winds during the last 12 hours of both the 0600 and 1600 CST trajectories were from the south.

The local (mesoscale) trajectories show southerly winds throughout the day in the Tulsa area. The early hours of the trajectory, 0800 and 0900 in particular, indicate that near calm conditions were present, but after 1100 the wind speeds were above 10 mph. The Oklahoma City rawinsonde release for 0600 CST measured southerly winds from the surface to 1,500 m MSL. The 1800 CST rawinsonde release measured southerly to southeasterly winds from the surface to 1,500 m MSL.

There were morning peaks in NO and $NO_2$ at both the Health Department and Post Office monitoring stations; however, the peaks at the Health Department were more clearly associated with morning traffic (Figure 4.35). These peaks were the result of the buildup of pollutant concentrations due to low wind speeds that were present during the early morning hours. The fact that the peaks were more variable and persistent at the Post Office site is probably due to the influence of sources in addition to the morning traffic. At 0900, when the windspeeds increased, both NO and $NO_2$ decreased at the Health Department. At the Post Office site the NO and $NO_2$ concentrations did not decrease until after 1200. Sites to the north of Tulsa also showed the influence of urban oxides of nitrogen. Sperry recorded the highest value of NO for the network (0.100 ppm) during hour 0600. The highest value for $NO_2$ at Sperry (0.027 ppm) occurred during hour 0800. A small increase in both NO and $NO_2$ was noted at the Vera site during hours 0900 and 1000. There was no change in oxides of nitrogen concentration evident at the other northern sites; values remained at or near background levels of 0.004 to 0.005 ppm.

On September 2, three sets of hydrocarbon grab samples were taken at the surface sites. Selected values from the morning and afternoon samples are given in Table 4.6. The 0500 to 0800 samples show a strong gradient of increasing acetylene, n-butane, propylene, and sum of hydrocarbons from upwind to downwind of the city. The Health Department had (based on an acetylene factor of 15.5) the highest percentage of hydrocarbons attributed to vehicular tailpipe emissions. The Sperry site, which is immediately north of the city, had the highest overall hydrocarbon sum, yet only 38 percent is attributed to tailpipe emissions. The Sperry sample contained a high percentage of low molecular weight alkanes (such as n-butane), which had slowly drifted northward from the oil refining production and storage facilities. The midmorning, 0800 to 1100 CST samples showed decreases in acetylene concentrations at all sites except Liberty Mounds, which increased slightly. At the Post Office, high concentrations of low molecular weight hydrocarbons (e.g., n-butane) were measured. Wind directions during this time were out of the south to southwest and high concentrations of low molecular weight alkanes were probably a result of emissions from the petrochemical complex. By midafternoon, the total NMHC measured at all of the northern sites was quite low. Acetylene (an indicator of tailpipe emissions)

TABLE 4.6. SEPTEMBER 2 HYDROCARBON SAMPLES, ppbC

| | Liberty Mounds | Health Department | Post Office | Sperry |
|---|---|---|---|---|
| (05 to 08 CST) | | | | |
| Acetylene | 1.0 | 25.0 | 30.0 | 34.4 |
| n-Butane | 36.0 | 40.4 | 60.4 | 196 |
| Propylene | 2.0 | 12.6 | 14.4 | 18.9 |
| Sum | 303 | 393 | 640 | 1,412 |
| % Tailpipe emissions | 5.1 | 99 | 73 | 38 |
| (08 to 11 CST) | | | | |
| Acetylene | 2.4 | 6.6 | 14.6 | 9.0 |
| n-Butane | 22.4 | 21.6 | 218.8 | 56.8 |
| Propylene | 0.0 | 4.0 | 19.2 | 5.1 |
| Sum | 350 | 349 | 1,199 | 313 |
| % Tailpipe emissions | 11 | 29 | 19 | 44 |

| | Sperry | Vera | Ochelata | Skiatook | Wynona |
|---|---|---|---|---|---|
| (13 to 16 CST) | | | | | |
| Acetylene | 6.4 | 2.4 | 1.2 | 1.0 | 0.4 |
| n-Butane | 15.6 | 9.2 | 10.8 | 9.6 | 6.0 |
| Propylene | 3.6 | 3.3 | 0.6 | 2.4 | 0.0 |
| Sum | 175 | 150 | 149 | 186 | 40 |
| % Tailpipe emissions | 57 | 25 | 12 | 8 | 15 |

was present at all sites, but decreased substantially at sites farther north of the city. The concentration of compounds such as propylene, which are very photochemically active, were also low compared to the concentrations during the morning in the city. There are three factors that probably contributed to the low concentrations in the afternoon samples: decreased automobile traffic during the afternoon; larger mixing volume causing more dilution than in the early morning; and removal by reaction.

With the steady southerly winds on September 2, Liberty Mounds represented the background, upwind station. At 0600 the Liberty Mounds ozone concentration was only 0.008 ppm. There was a rapid rise following 0700 CST, however, and by 0900 the concentration was very near that day's maximum value of 0.056 ppm (Figure 4.36). Once the ozone concentration reached approximately 0.050 ppm, it remained very stable until 1800 CST. The same is true for the Health Department and Post Office ozone data. The fact that relatively low daily maximum concentrations were attained early in the morning and that concentrations near the maximum level were maintained during the photochemically active portion of the day suggests that the primary source of the ozone measured at Liberty Mounds, the Health Department, and the Post Office sites on September 2 was downward mixing of air that had been isolated above the radiation inversion. Investigation of the aircraft data (Figures 4.39 and 4.40) reveals that during the September 2 morning spiral at Liberty Mounds, approximately 0.050 ppm of ozone was measured at an altitude of 1,100 ft MSL. An overall ozone background concentration based on both the vertical spiral and the horizontal legs of the morning flight was approximately 0.060 ppm.

During September 2, the northern sites were under the influence of steady southerly winds from approximately 0900 through the remainder of the day. At Sperry and Vera the concentration of ozone also rose sharply during the early morning as it had at the southern site. However, the concentrations continued to rise and reached a daily maximum at hour 1200. At both Sperry and Vera the maximum hourly ozone concentration was 0.094 ppm. At Ochelata the ozone diurnal pattern was very similar to that of the upwind station until hour 1200. A rapid increase early in the morning was followed by 4 hours of stable ozone concentrations of about 0.055 ppm. However, the 1300 ozone concentration increased substantially, and the daily maximum of 0.108 ppm was reached at 1400 CST. The local trajectories for September 2 indicate that an air mass left Tulsa at approximately 1100 hours, was in the vicinity of Vera between 1200 and 1300, and arrived at Ochelata at hour 1400.

Concentration/distance plots are shown in Figure 4.49. During the times illustrated, the wind direction across the network was from the south. The 0900 plot shows a fairly uniform background ozone concentration over the entire monitoring network. The plots for hours 1100, 1200, 1300, and 1400 show the plume movement north to Ochelata. These data all support the concept of ozone formation and transport at the surface from Tulsa to the north.

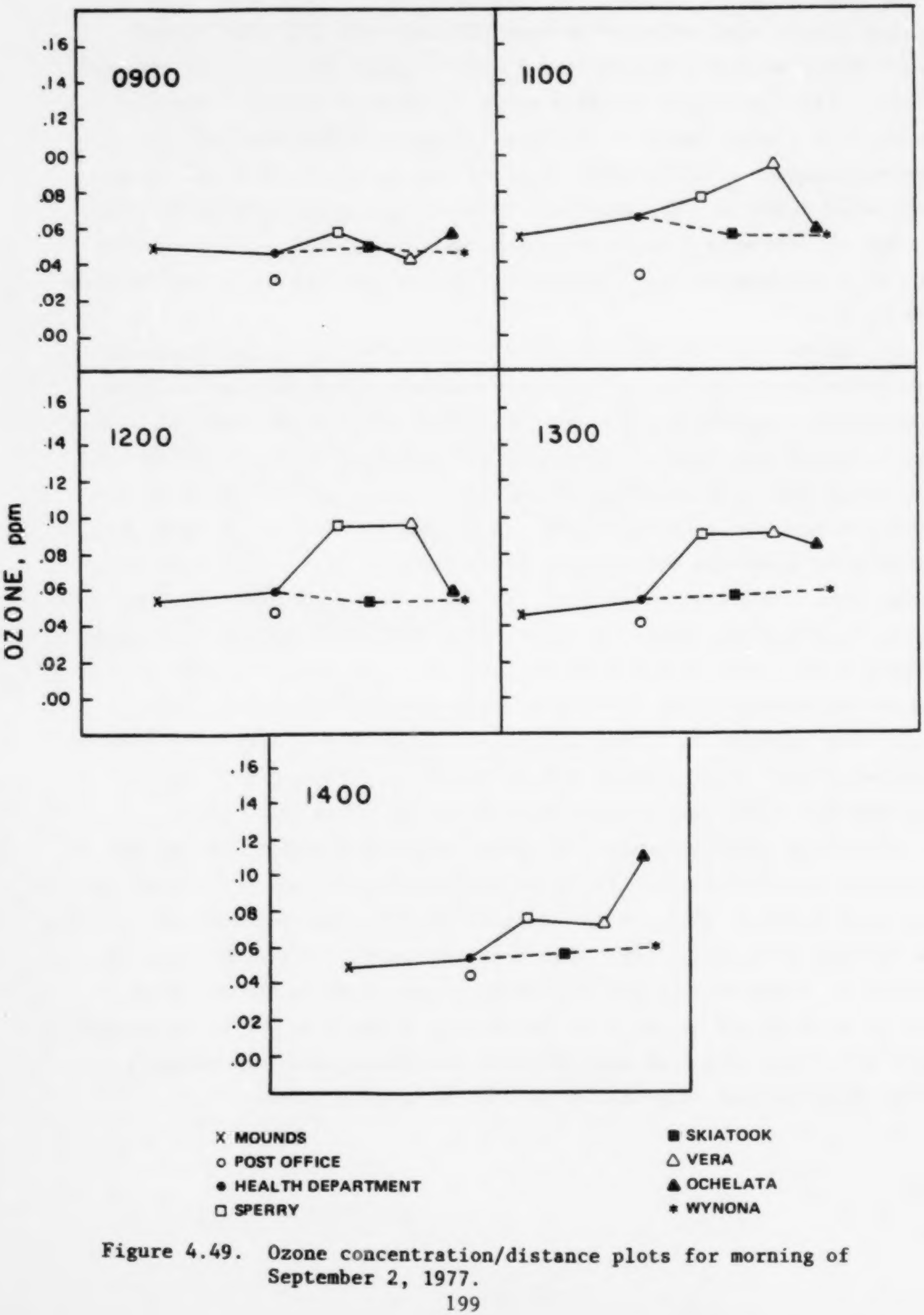

Figure 4.49. Ozone concentration/distance plots for morning of September 2, 1977.

The afternoon aircraft data in Figure 4.42 also show an ozone plume leaving Tulsa at 2,500 ft MSL. The data on the horizontal legs of the afternoon flight were collected between 1230 and 1400 CST. The highest concentrations were measured on legs 5 and 7 between approximately 1320 and 1400 CST. Leg 5 was flown slightly south of Ochelata and leg 7 was flown approximately 8 miles north of Ochelata. These data indicate that the downwind transport of urban ozone occurred both at the surface and at an elevation of 2,500 ft. The afternoon vertical spiral indicates that ozone was mixed on September 2 up to approximately 5,000 ft MSL. This suggests that the ozone plume existed continuously in the vertical up to altitudes of 5,000 ft MSL.

At both Skiatook and Wynona, rapidly increasing ozone concentrations were measured early in the day that were similar to the increase in ozone concentration measured at Liberty Mounds. Both stations measured increasing ozone concentrations that stabilized at approximately 0.055 at 1000 CST. Later in the day, however, sharp increases in the ozone concentration were measured at both Skiatook and Wynona. A maximum hourly average ozone concentration of 0.080 ppm was measured at Skiatook at 1500 CST. At Wynona, a maximum ozone concentration of 0.082 ppm was measured at 1700 CST. The concentration/distance plots for hours 1500, 1600, 1700, and 1800 are shown in Figure 4.50. These plots show the substantial increase in ozone at Skiatook and Wynona during hours when ozone was on the decline at other sites. This behavior is likely a direct consequence of a wind shift from a direction of 170° (during hours 1300 and 1400) to 130° and 150° (during hours 1500 and 1600) that altered the path of the urban ozone plume.

In summary, a large urban ozone plume began to form by 1000 and was transported north of Tulsa. The plume height extended from the surface up to at least 2,500 ft MSL. The presence of the plume was noted at the Ochelata site up until hour 1400. After this hour, the surface winds shifted from southerly to southeasterly and carried the ozone plume to the northeast sites of Skiatook and Wynona. In the absence of the wind shift, it is very likely that ozone data from both Skiatook and Wynona would have shown a diurnal ozone pattern very similar to that of Liberty Mounds.

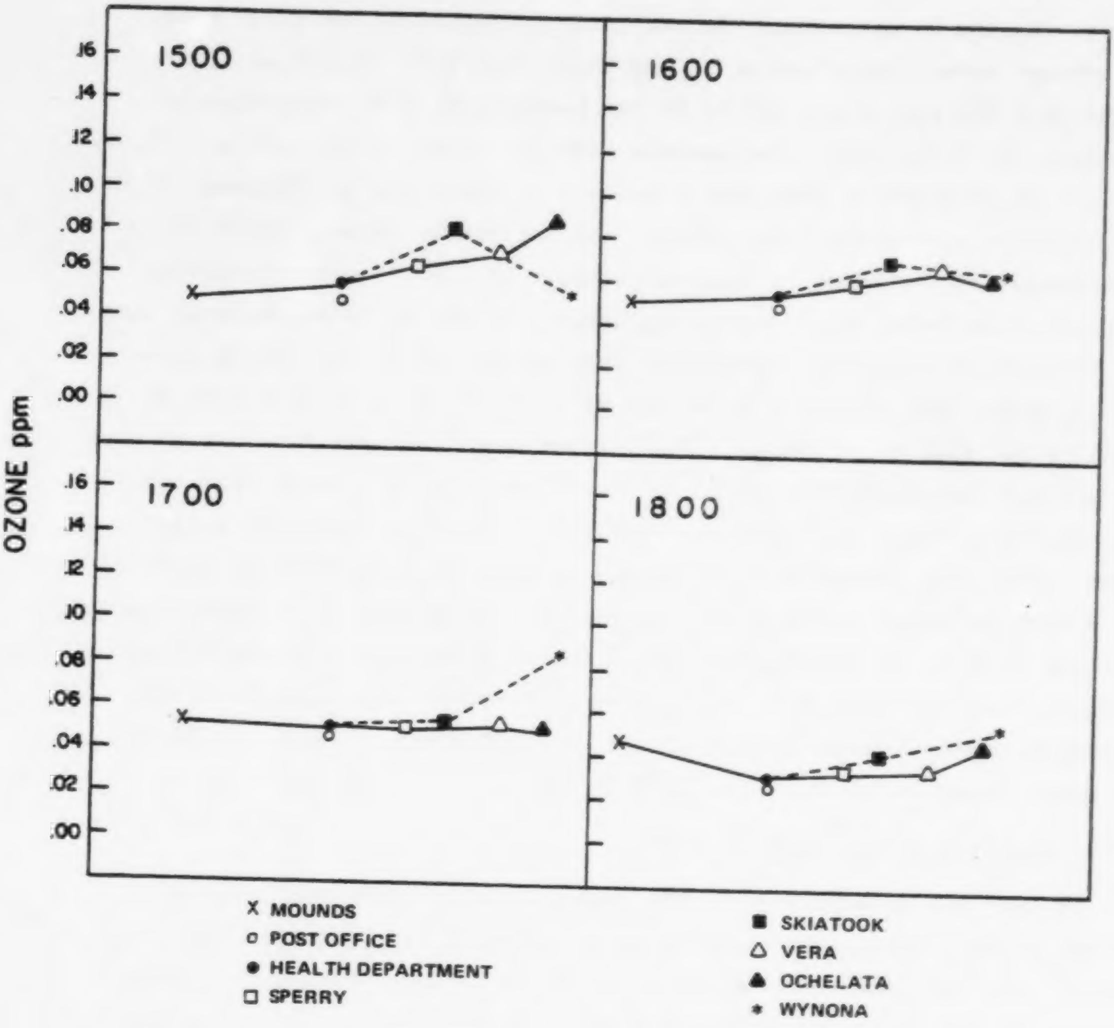

Figure 4.50. Ozone concentration/distance plots for the afternoon of September 2, 1977.

The presence of southerly winds and good solar radiation again offers the possibility of estimating the net ozone formation of the Tulsa area. The average ozone concentration during hours 1000 and 1100 CST at Liberty Mounds of 0.055 ppm is assumed to be the background ozone concentration affecting the Tulsa area. The maximum downwind ozone concentration of 0.105 measured at 1400 CST at Ochelata is assumed to represent the maximum ozone concentration within the urban plume. The difference between these two measurements of 0.050 ppm is then an estimate of the net ozone formation resulting from Tulsa emissions on September 2 at the surface. Because there was an aircraft flight on September 2 that showed an apparent ozone plume leaving Tulsa, the net ozone formation as a result of Tulsa emissions at 2,500 ft can also be estimated. The maximum ozone concentration measured on the aircraft during the afternoon was 0.156 ppm. It is assumed that the true impact of Tulsa emissions was confined to the area included in the plume itself and, therefore, the average concentration outside the plume on the afternoon flight was used to represent the background ozone concentration at 2,500 ft MSL. On September 2 this downwind afternoon background ozone concentration was 0.078 ppm. The difference between the maximum and the average background ozone concentrations of 0.078 ppm is an estimate of the net ozone formation of Tulsa at 2,500 ft MSL.

### 4.5.4 Analysis of September 3, 1977

By 0700 EST on September 3, the high-pressure center that was over western North Carolina and Virginia on September 2 had weakened (Figure 4.29c). The Oklahoma area, however, was still influenced by anticyclonic circulation and south and southeast winds were measured in the Tulsa area. The synoptic trajectories shown in Figure 4.30 indicate directional motion on September 3 similar to that of September 2 but with slower wind speeds. The local-scale trajectories show southerly winds in Tulsa on September 3 (Figure 4.31). There were calm conditions indicated during hours 0700 and 0800. The skies remained mostly clear during the morning but solar radiation was depleted during the afternoon (Figure 4.34).

Since September 3 was a Saturday there was not a clear traffic peak of NO or $NO_2$ at either the Post Office or Health Department sites. There were relatively high concentrations of NO and $NO_2$ throughout the morning hours at the Health Department and, as expected, very low ozone concentrations accompanied these high concentrations. At the Post Office site, NO and $NO_2$ concentrations were greater during the middle of the day than at any other time.

On September 3, three sets of hydrocarbon grab samples were taken at the surface sites. Selected values from the morning and afternoon samples are given in Table 4.7. As was true on September 2, a gradient of increasing acetylene, n-butane, propylene, and sum of hydrocarbons from upwind to downwind sites was present on September 3. Generally, however, the concentrations of species were lower on Saturday, September 3, than they were on Friday, September 2. Exceptions to this statement were the 0500 to 0800 samples at Liberty Mounds, which may have measured some industrial emissions of Tulsa because of early morning northerly winds. At Sperry, large amounts of low molecular weight alkanes were measured during the 6-9 CDT measurement period. The percentage of sample attributable to vehicular tailpipe emissions was also less in the early morning Saturday samples. The afternoon samples taken at northern sites showed concentrations much lower than those of morning samples. This was expected due to increased afternoon dilution.

At Liberty Mounds on the morning of September 3, the ozone concentration fell to zero at 0500 CST suggesting that a source of ozone-destructive material was affecting the area. The third highest 0500 to 0800 CST average $NO_x$ (0.018 ppm) of all days at Liberty Mounds was measured on September 3. In addition, the $NO_x$ concentrations of hours 0300, 0400, and 0500 were unusually high for Liberty Mounds. A northwesterly wind of 2 mph was measured at Liberty Mounds during the hours of 0400 and 0500 and perhaps air was brought in from urban areas, causing the drop in ozone at Liberty Mounds.

By 0900 southerly winds were established, and the 0800 to 1100 CST hydrocarbon and $NO_x$ concentrations at Liberty Mounds were more in line with average values. The persistence of southerly flow after 0900 caused Liberty Mounds to experience background conditions. The ozone concentration rose quickly to 0.063 ppm by hour 1000, then remained steady with average values between 0.060 ppm and 0.065 ppm until late in the afternoon.

TABLE 4.7. SEPTEMBER 3 HYDROCARBON SAMPLES, ppbC

| | Liberty Mounds | Health Department | Post Office | Sperry |
|---|---|---|---|---|
| (05 to 08 CST) | | | | |
| Acetylene | 2.0 | 11.0 | 12.0 | 25.6 |
| n-Butane | 63.6 | 26.4 | 40.0 | 412.8 |
| Propylene | 2.6 | 4.8 | 6.3 | 15.0 |
| Sum | 620 | 285 | 367 | 3,078 |
| % Tailpipe emissions | 5 | 60 | 51 | 13 |
| (08 to 11 CST) | | | | |
| Acetylene | 3.6 | 6.6 | 8.2 | 17.4 |
| n-Butane | 24.4 | 25.2 | 146.4 | 131.2 |
| Propylene | 4.8 | 1.8 | 10.8 | 10.2 |
| Sum | 173 | 216 | 687 | 842 |
| % Tailpipe emissions | 32 | 47 | 18 | 32 |

| | Sperry | Vera | Ochelata | Skiatook | Wynona |
|---|---|---|---|---|---|
| (13 to 16 CST) | | | | | |
| Acetylene | - | 5.2 | 1.0 | 1.0 | 2.0 |
| n-Butane | - | 21.2 | 8.4 | 7.6 | 9.2 |
| Propylene | - | 0.0 | 3.6 | 16.2 | 0.0 |
| Sum | - | 150 | 107 | 121 | 91 |
| % Tailpipe emissions | - | 54 | 14 | 13 | 34 |

At the Post Office site the ozone concentrations averaged approximately 0.065 ppm throughout the day except for a decrease during hours 1300 and 1400. This decrease was accompanied by increases in both NO and $NO_2$. At the Health Department site the concentrations of ozone averaged approximately 0.075 ppm throughout the day. The slightly slower winds of September 3 may have allowed sufficient time for production of ozone in excess of the decrease caused by NO titration of ozone. This would explain why the average ozone concentration was slightly higher in the city than at Liberty Mounds on September 3. The background ozone concentration at Liberty Mounds on September 3 was only slightly greater than the background measured on September 2. The background ozone concentration at 2,500 ft MSL obtained during the morning aircraft flight of September 3 was also higher than the background measured aloft on September 2 by approximately 0.02 ppm.

The diurnal ozone profiles for Liberty Mounds, the Post Office, and the Health Department sites for September 3 are very similar to those of September 2. The rapidly increasing ozone concentrations between 0700 and 0900, followed by steady concentrations, imply that these stations were measuring predominantly background concentrations present in air that was mixed down to the surface from above the radiation inversion.

The morning background ozone concentration measured by the aircraft during the September 3 spiral at Liberty Mounds was approximately 0.070 ppm (Figure 4.44). At an altitude of 3,700 ft there was a maximum ozone concentration of about 0.08 ppm on the vertical spiral. A maximum ozone concentration of approximately 0.080 ppm, at nearly the same altitude, had also been measured during the Liberty Mounds spiral of September 2. However, the background on September 2 was only about 0.050 ppm and the maximum at 2,800 ft appeared to be part of a layer. With the increased background on September 3, the ozone and maximum at 2,700 ft does not appear as a distinct layer as it did on September 2. The background ozone concentration at 2,500 ft on September 3, as measured on the horizontal legs of the morning flight (Figure 4.45), was approximately 0.080 ppm. It is evident that the background ozone concentrations aloft were greater on September 3 than on September 2. The afternoon flight of September 2 had shown concentrations of ozone of approximately 0.080 ppm on those parts of the horizontal legs that were clearly outside of the urban plume. These findings suggest that ozone at concentrations as high as 0.08 ppm may have persisted at altitudes of 2,500 ft throughout the night of September 2.

At each of the downwind stations, ozone concentrations increased rapidly after hour 0700 until 1000. By 1000, the ozone concentration at Sperry and Vera was approximately 0.030 ppm higher than the background concentration measured at the upwind station. The concentrations stabilized somewhat soon after hour 1000; the maxima for the day was not measured until 1300 at either Sperry or Vera. At Ochelata the ozone concentration attained by 1000 was only slightly greater than the background site concentration at the same hour; maximum for the day (0.093 ppm) occurred at 1500. As was the case on September 2, the maximum concentration at Ochelata was measured 2 hours later than at Sperry or Vera. The maximum hourly average ozone concentration at Sperry was 0.116; at Vera, 0.126 ppm. These data imply that the full impact of Tulsa emissions on ozone formation was not observed at Ochelata on September 3. This is possibly due to the presence of slower wind speeds or to the midafternoon wind shift, which may have kept the highest ozone concentrations of the Tulsa plume from reaching Ochelata.

The concentration/distance plots shown in Figure 4.51 best show the behavior of the plume ozone after hour 1300. The ozone distribution at hour 1400 indicates that Sperry and Vera were measuring the Tulsa plume and all other stations were measuring concentrations near the background. A wind shift from the south to the southeast occurred at hour 1400 and continued for several hours. The ozone concentrations measured at Sperry and Vera began to decrease, while at Skiatook and Wynona an increase in ozone concentration occurred during hour 1500. The winds continued to shift around to the east and the ozone at Wynona increased to a maximum of 0.098 ppm by 1700. Both Skiatook and Wynona measured daily maximum ozone concentrations late in the afternoon after the wind had shifted.

The aircraft data again showed a very well defined afternoon ozone plume to the north of Tulsa (Figure 4.47). The maximum ozone concentration measured during this flight was 0.207 ppm on leg 3 at a distance approximately 20 miles north of the center of Tulsa. That flight leg occurred between approximately 1302 and 1318 CST. The maximum ozone concentration measured at the surface was at Vera, a location almost directly under the flight track mentioned above. Therefore, there was no apparent time lag between the arrival of the plume at 2,500 ft and the surface. The path followed by the plume on September 3 was quite different from the very straight plume observed on September 2. The wind speeds were slower on September 3, and the meandering path of the plume may be associated with the slower winds.

Once again the net ozone production due to Tulsa can be estimated. Southerly and southeasterly winds were present throughout the day in Tulsa and therefore the average of the 1000 and 1100 CST ozone concentrations at Liberty Mounds of 0.063 ppm was assumed to be representative of the background ozone concentration in the Tulsa area on September 3. The maximum downwind ozone concentration measured on September 3 was 0.126 ppm, which

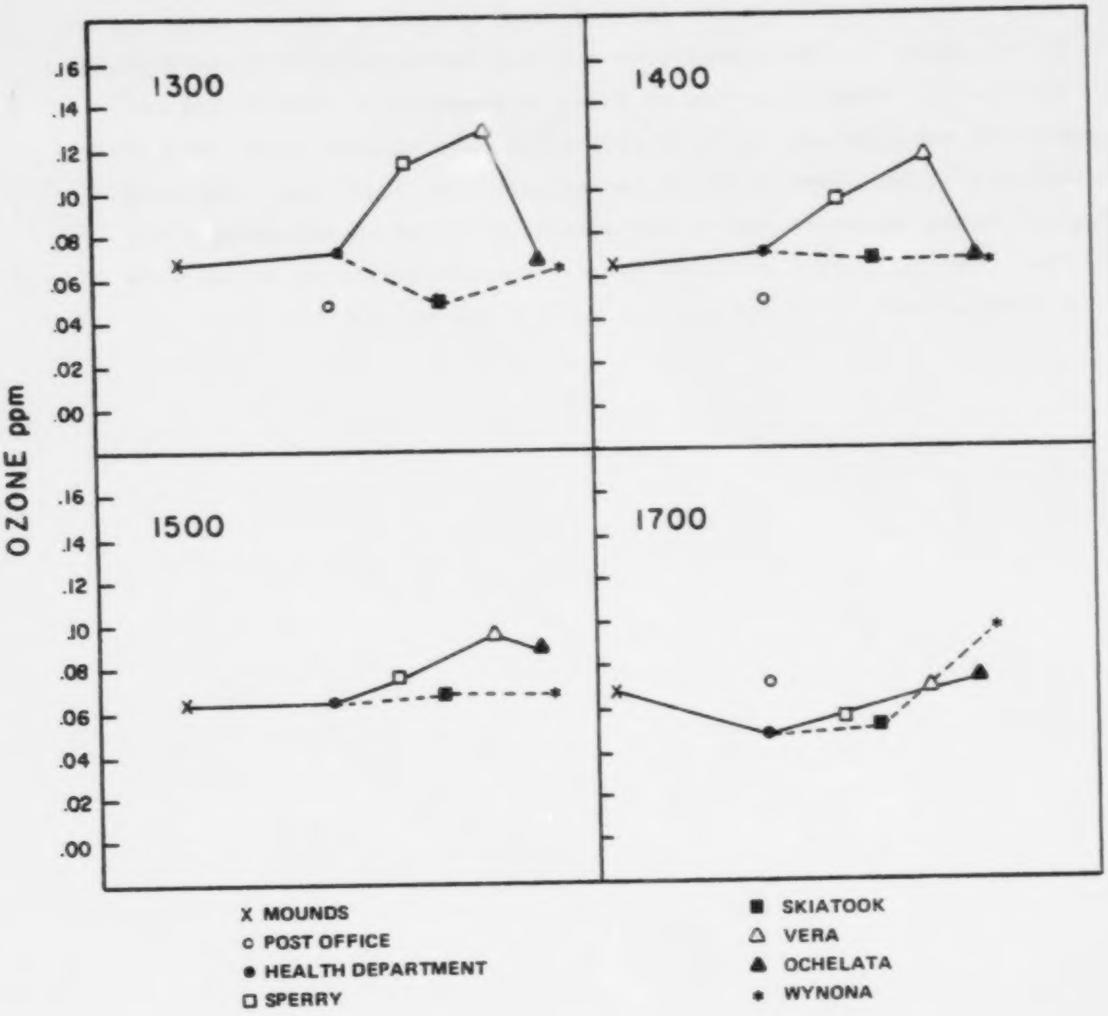

Figure 4.51. Ozone concentration/distance plots for September 3, 1977.

occurred at 1300 at Vera. The difference between these two measurements of 0.063 ppm is assumed to represent the net ozone formation due to Tulsa emissions on September 3. There were also aircraft measurements made on September 3 and the net ozone formation of Tulsa as measured at 2500 ft MSL was determined in the same way as for September 2. The maximum ozone concentration measured on September 3 aboard the aircraft was 0.207 ppm. The mean background ozone concentration on the afternoon flight of September 3 was 0.091 ppm. The difference of 0.116 ppm is then assumed to be an estimate of the net ozone formation as measured at 2500 ft MSL on September 3.

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12. Washington State University, Measurement of Light Hydrocarbons and Oxidant Transport, Houston Study 1976, Environmental Protection Agency Report No. EPA-600/3-78-062.

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## Section 4.0

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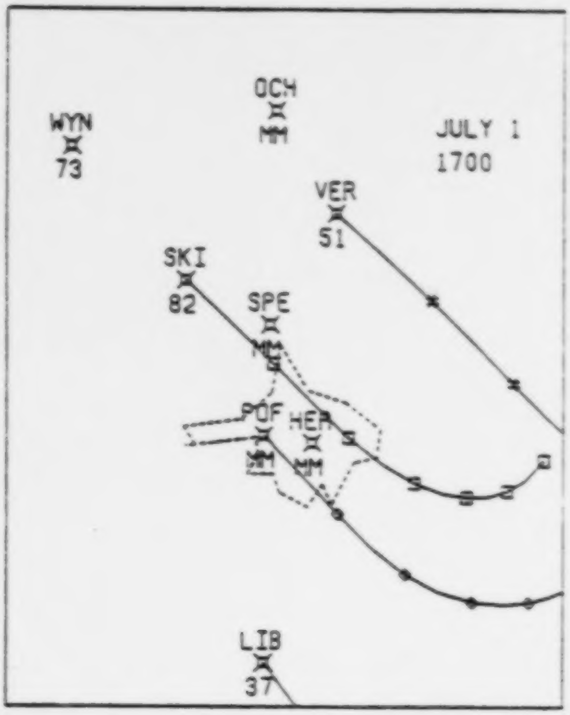
2. P. J. Sampson, "Nocturnal Ozone Maxima," Atmospheric Environment, 12, 951 (1978).

# APPENDIX A

# MESOSCALE AIR PARCEL TRAJECTORIES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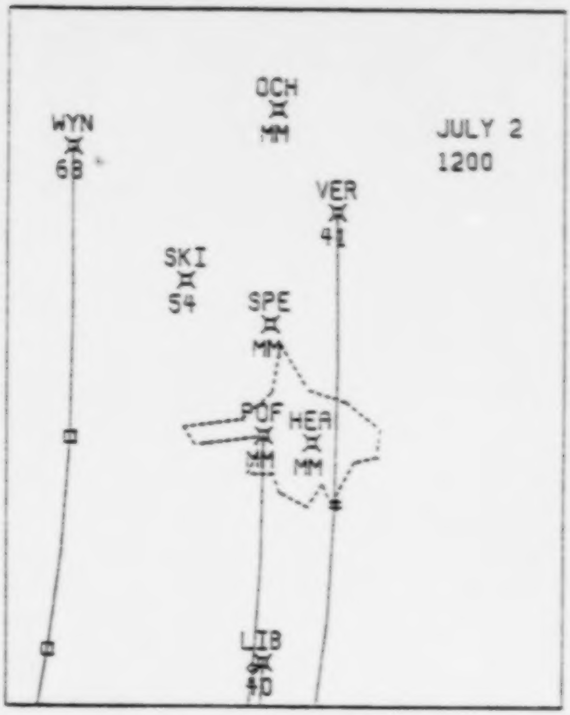
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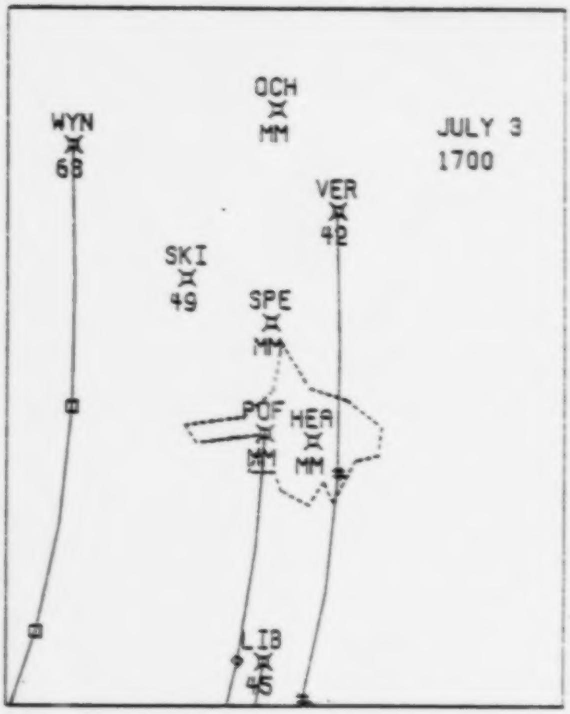
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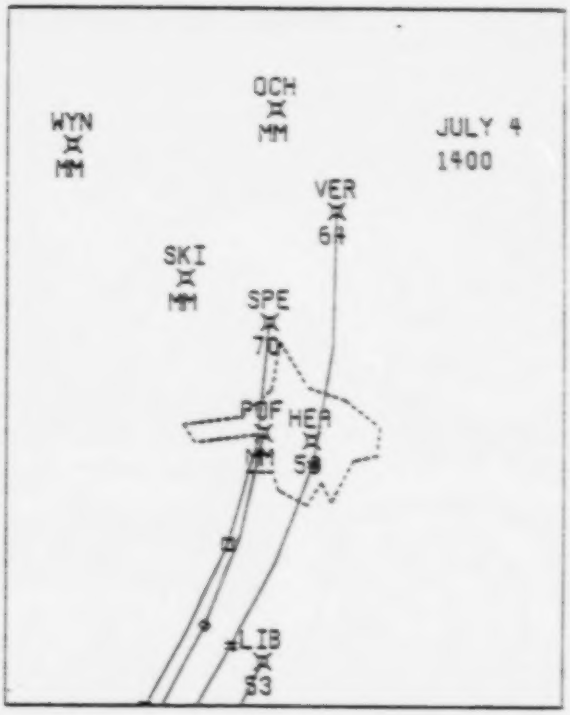
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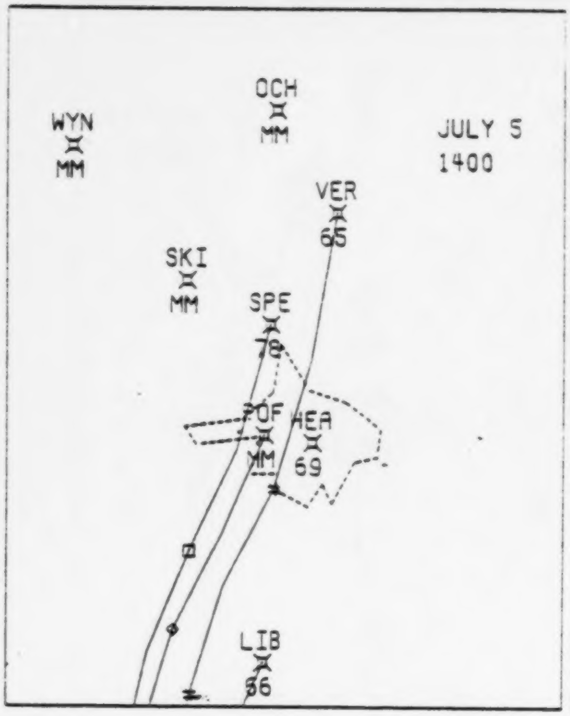
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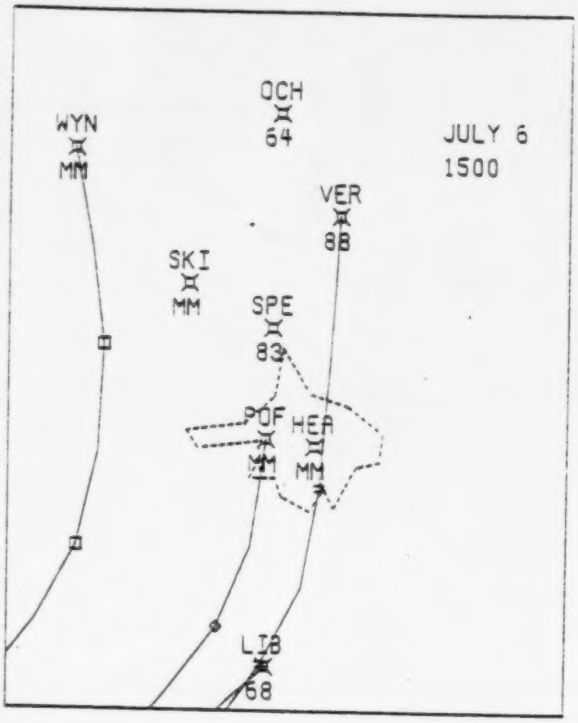
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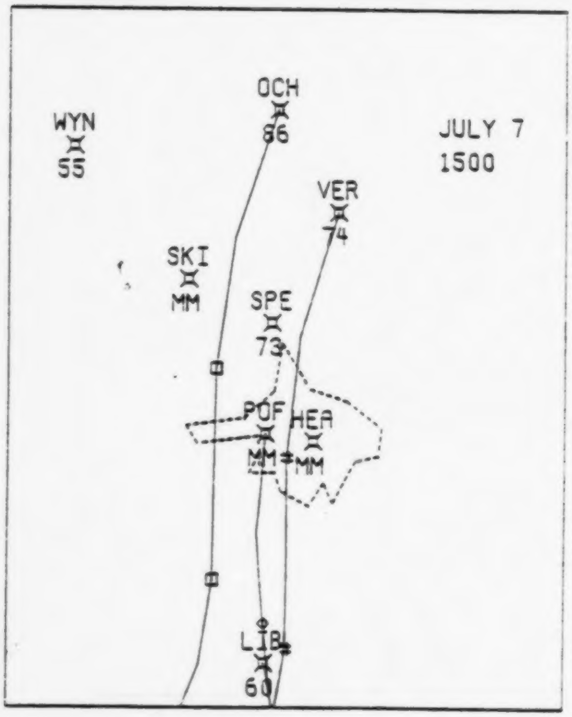
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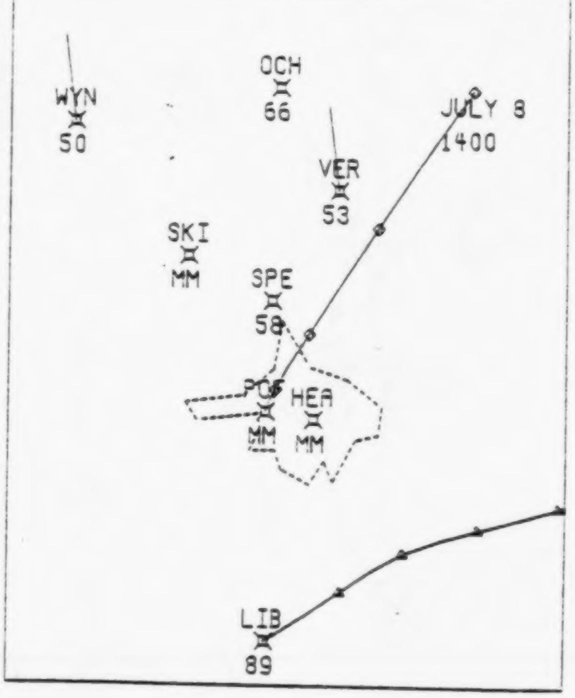
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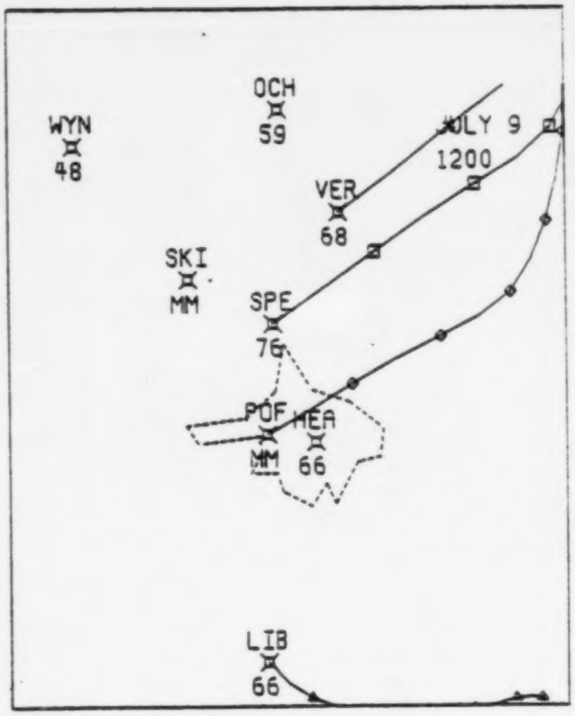
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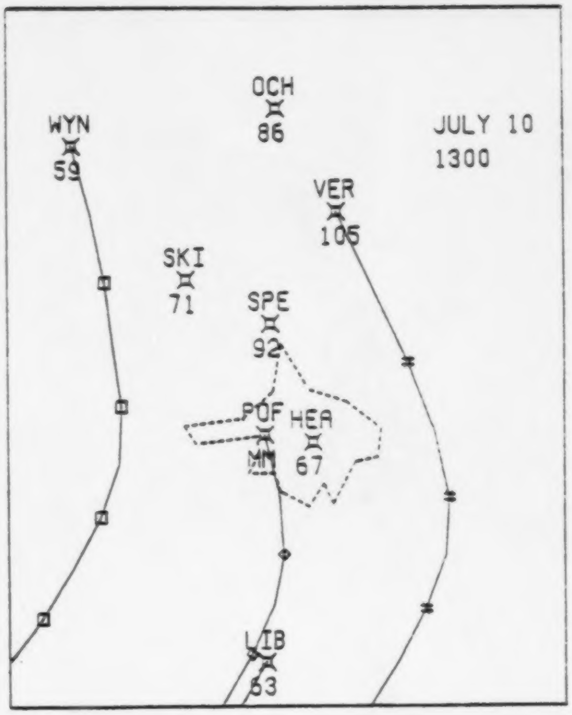
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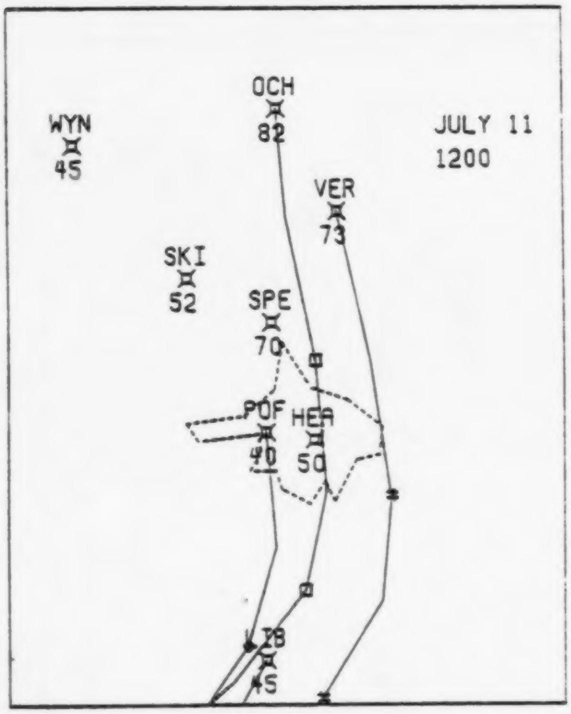
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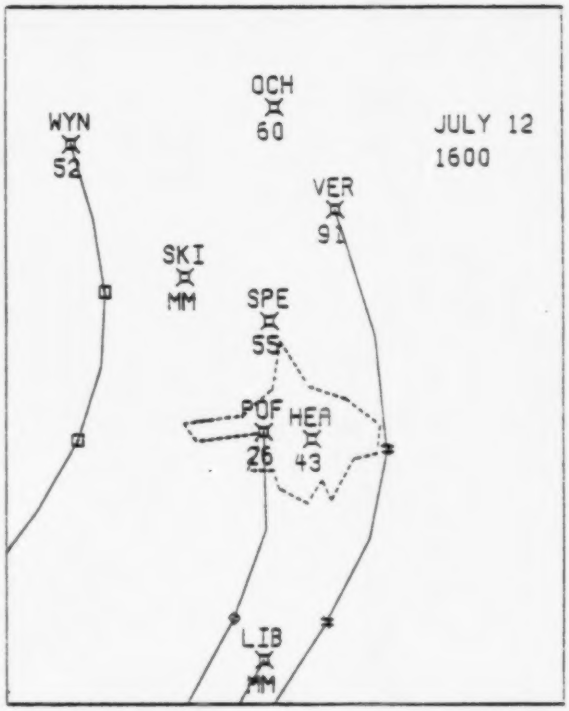
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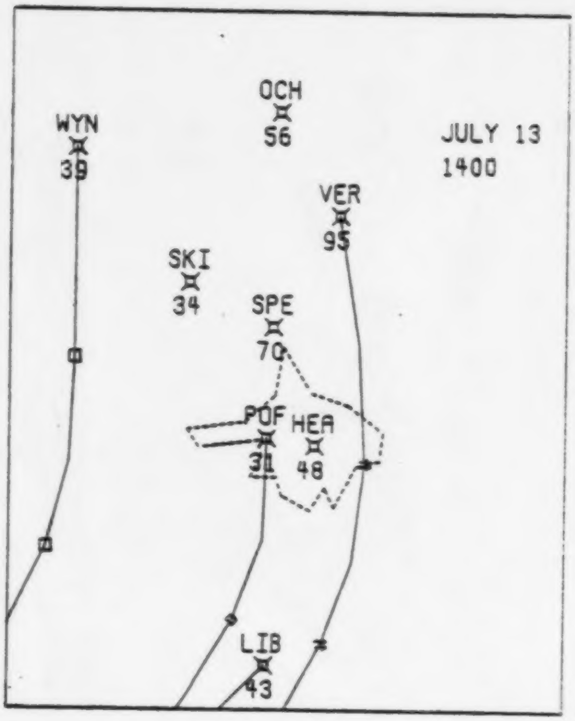
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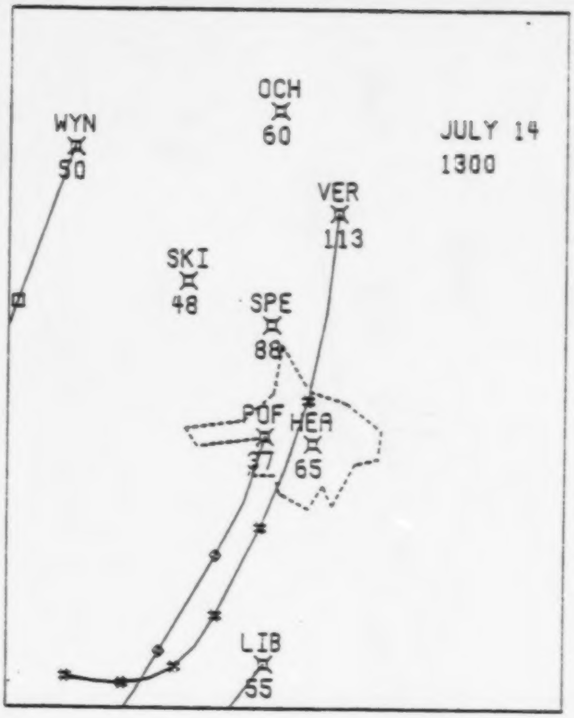
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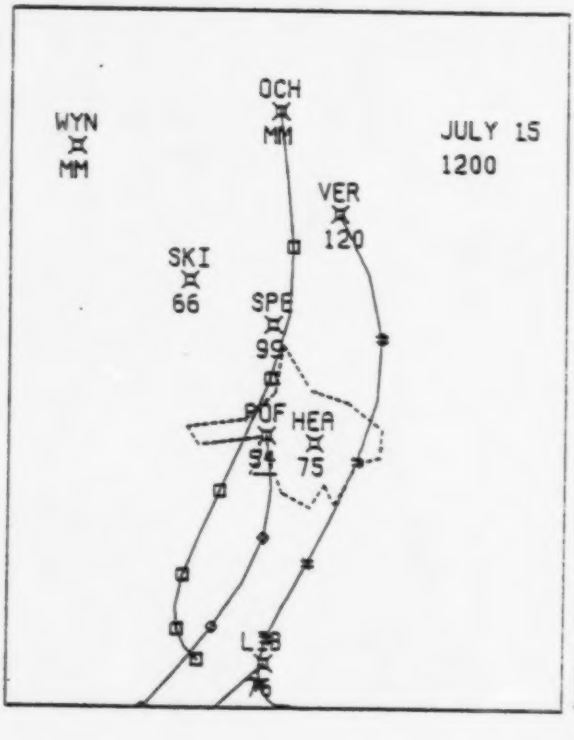
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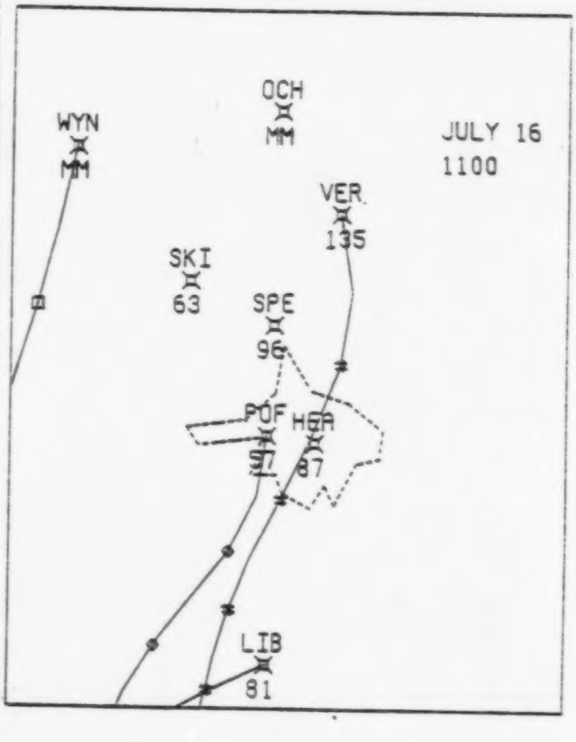
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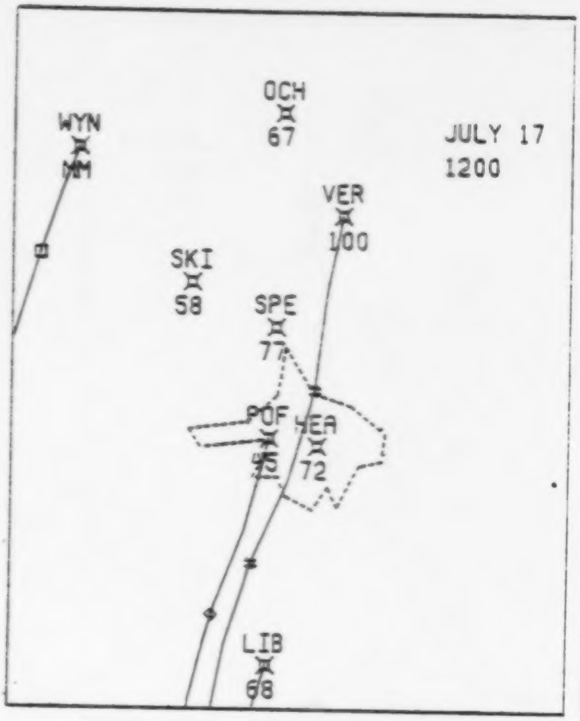
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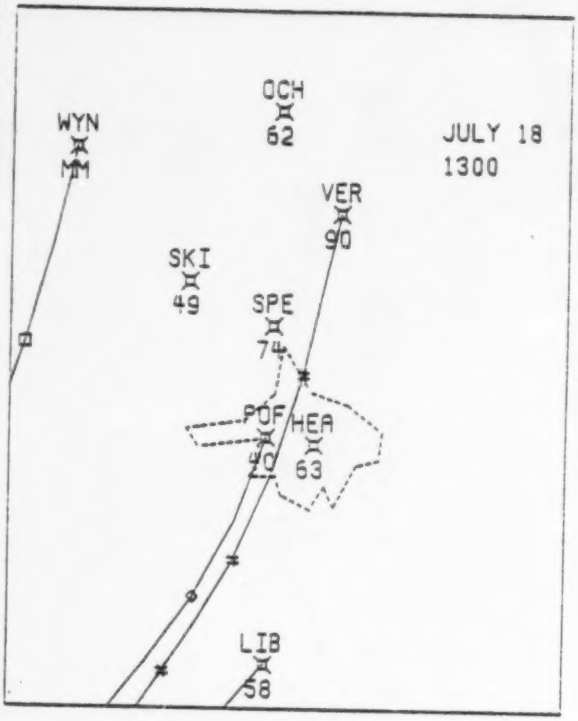
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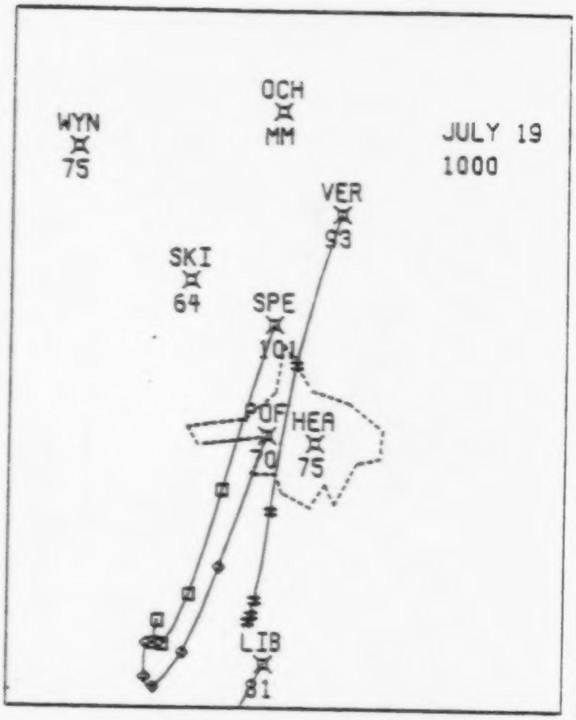
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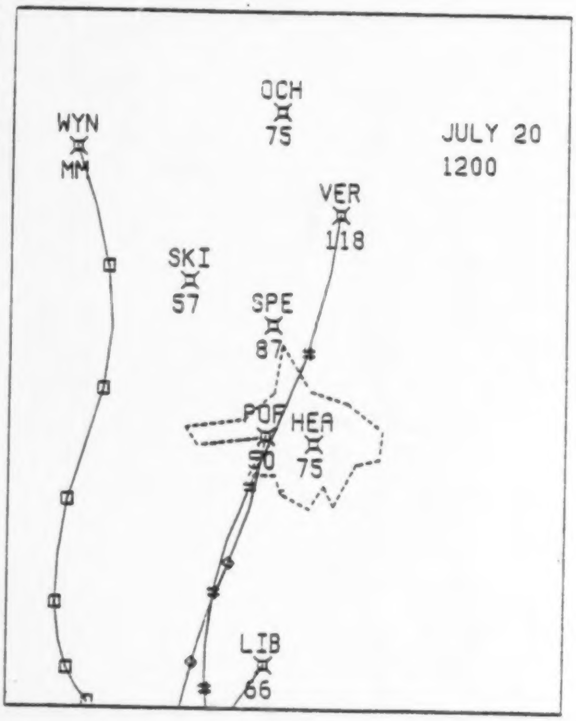
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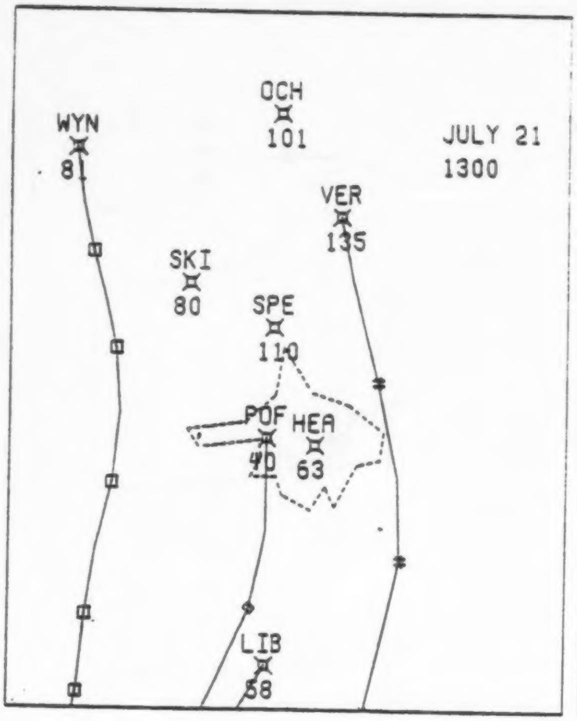
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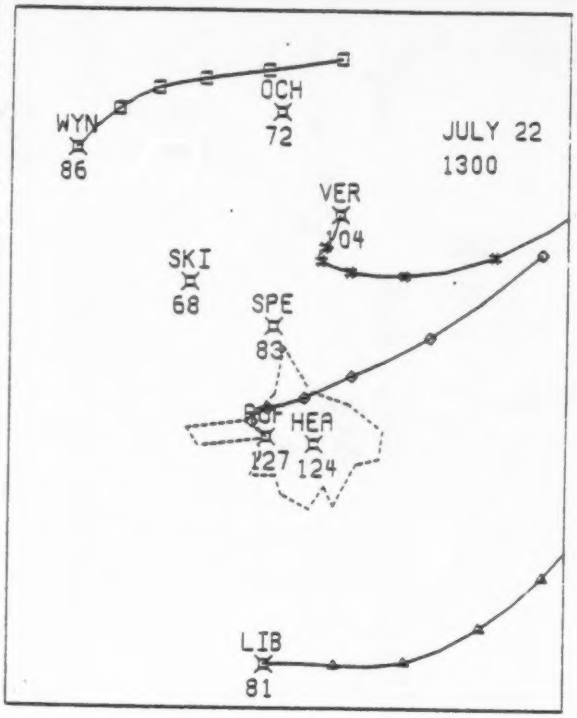
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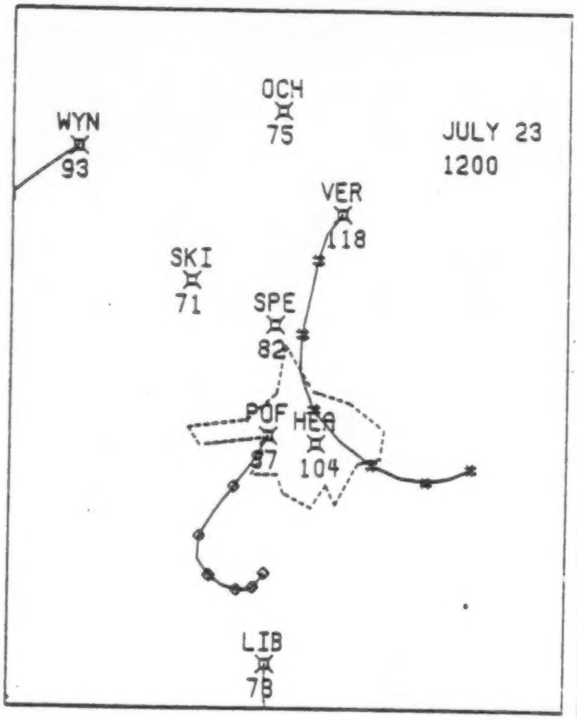
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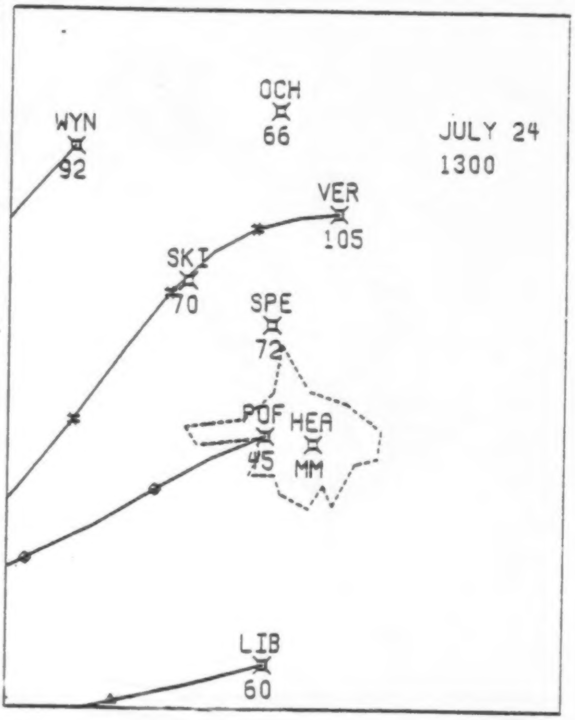
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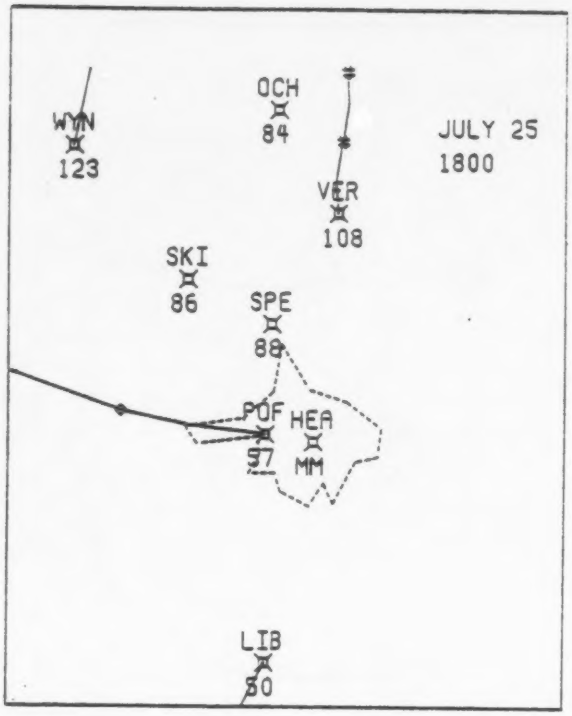
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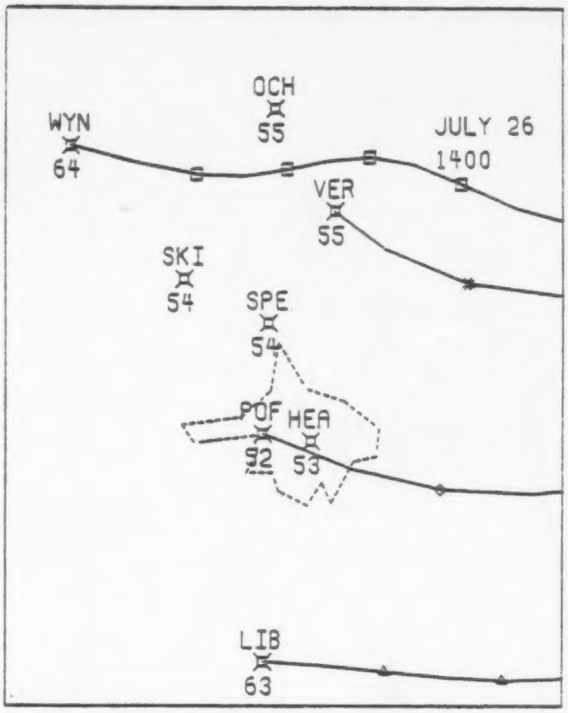
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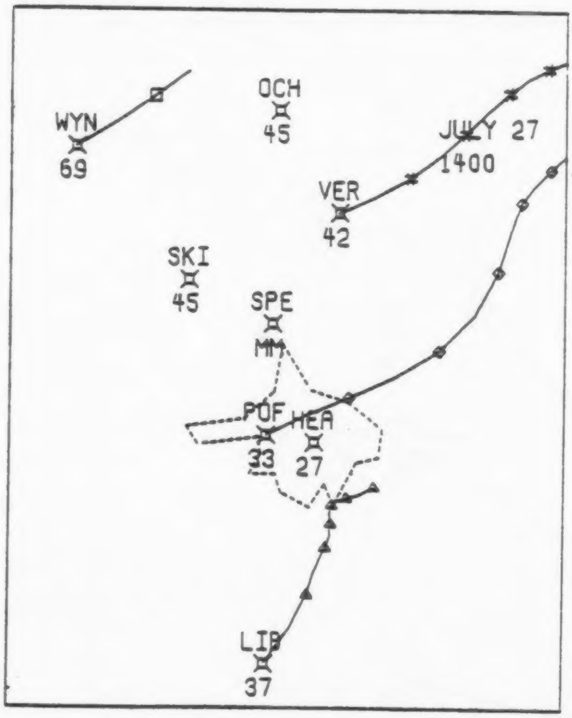
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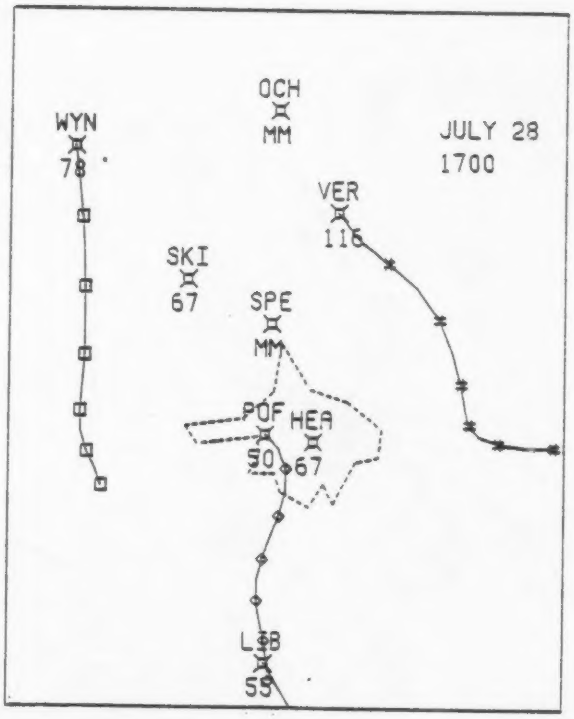
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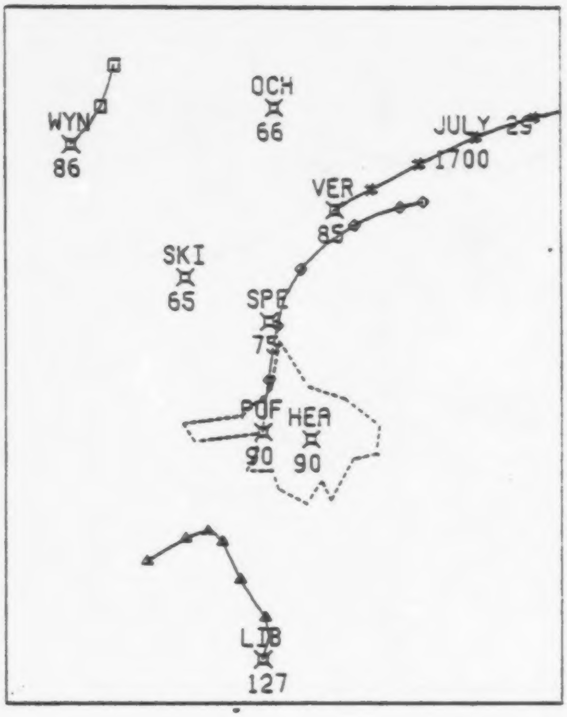
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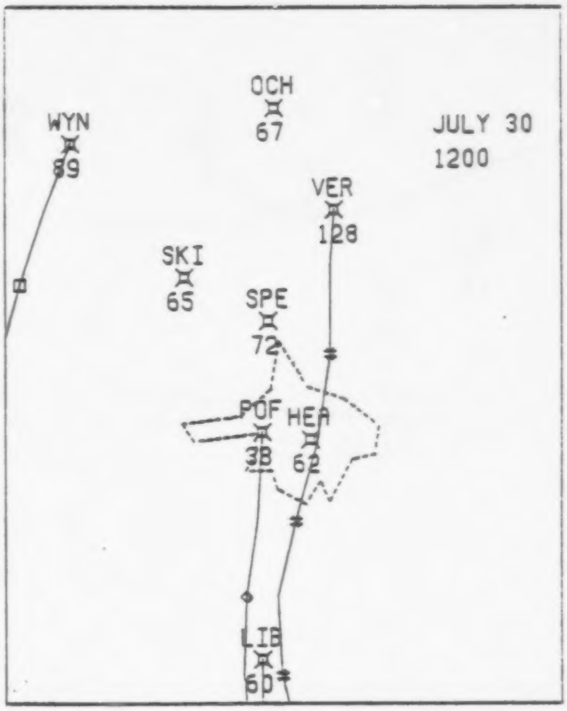
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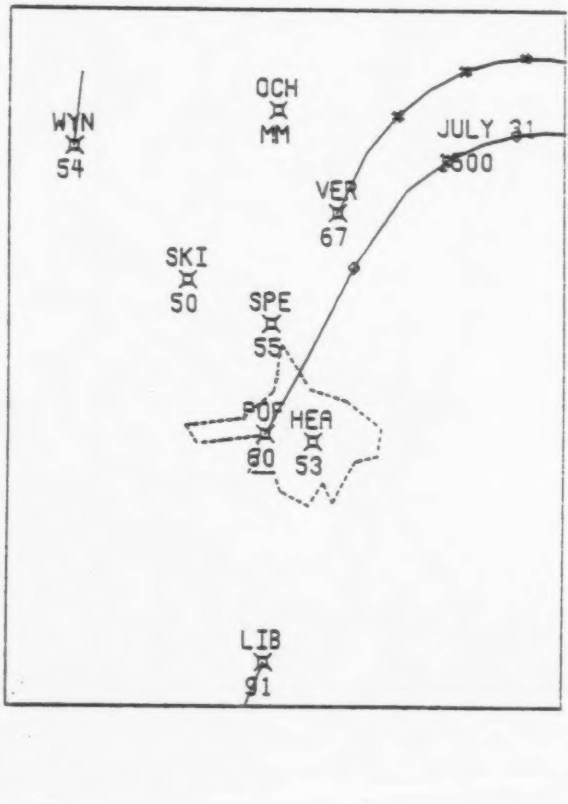
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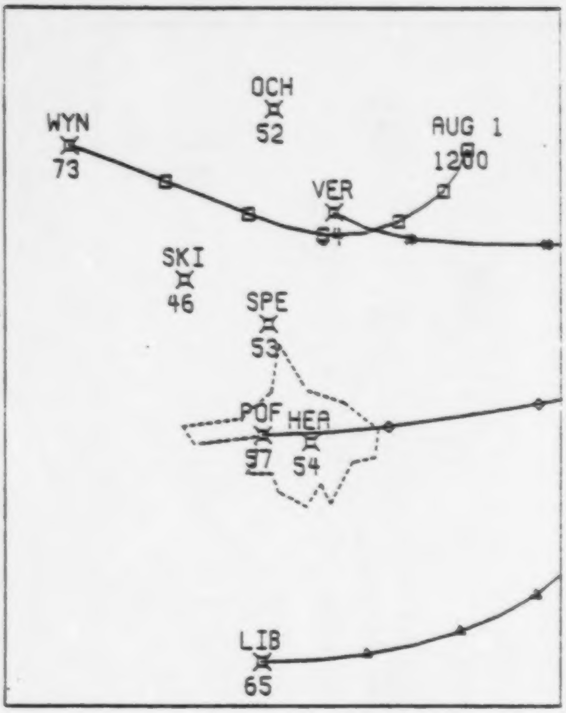
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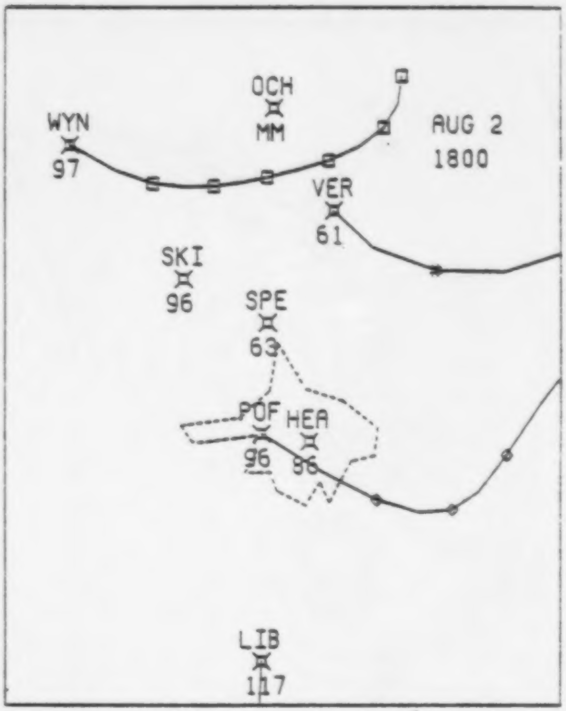
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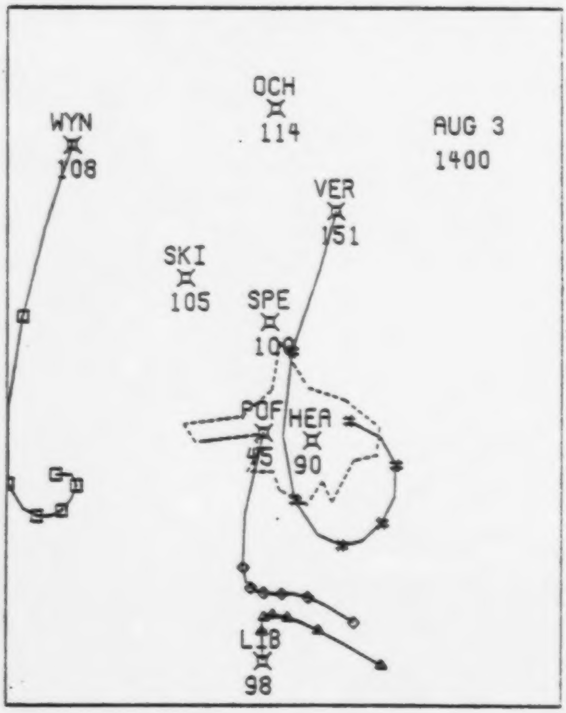
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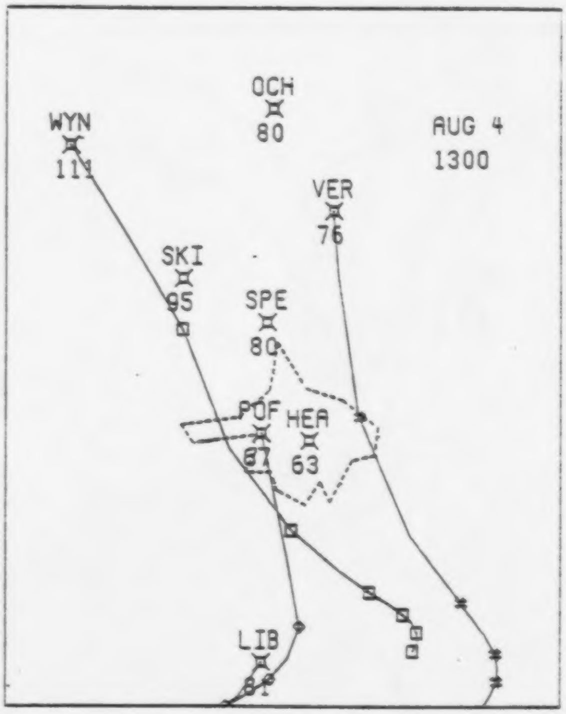
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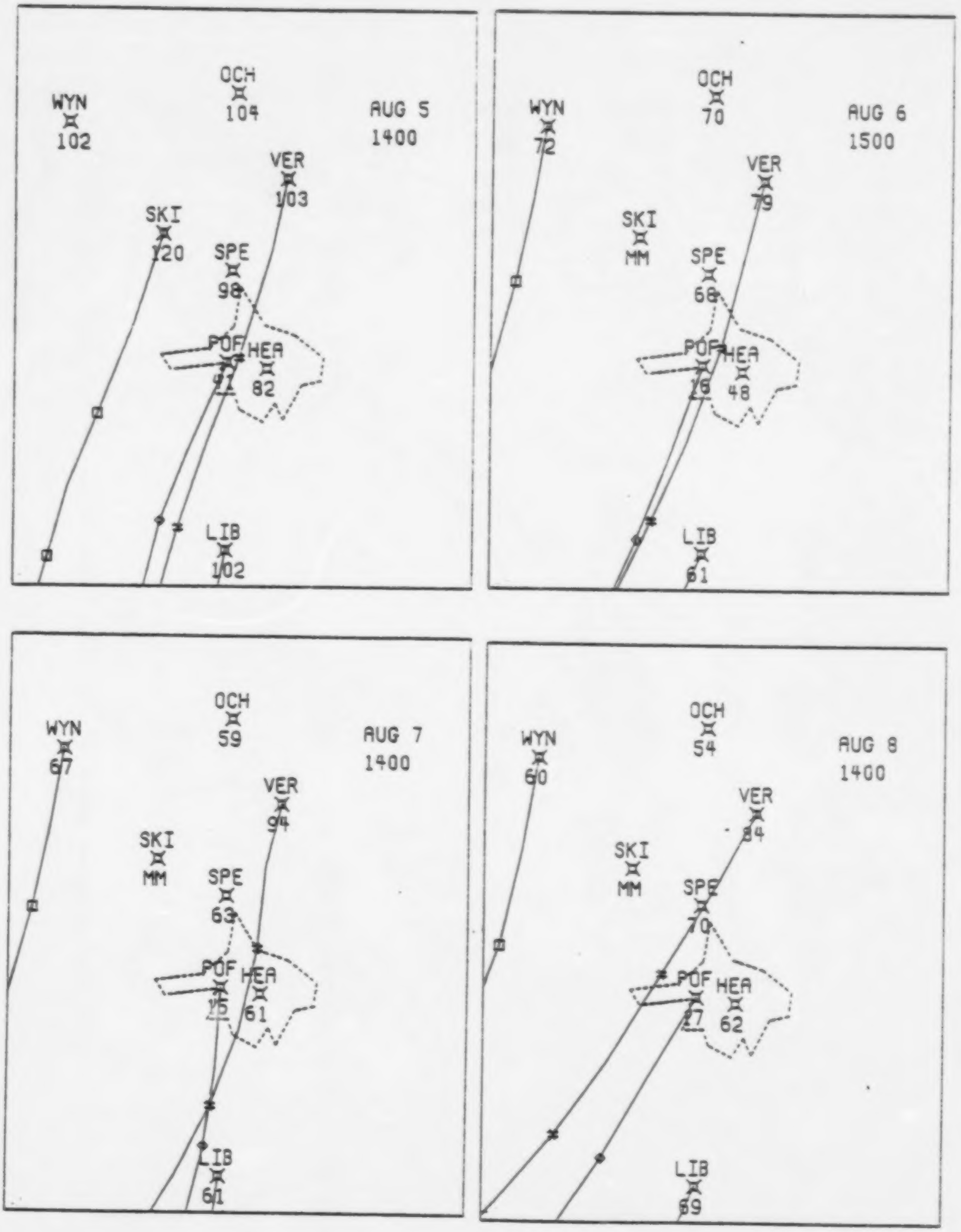
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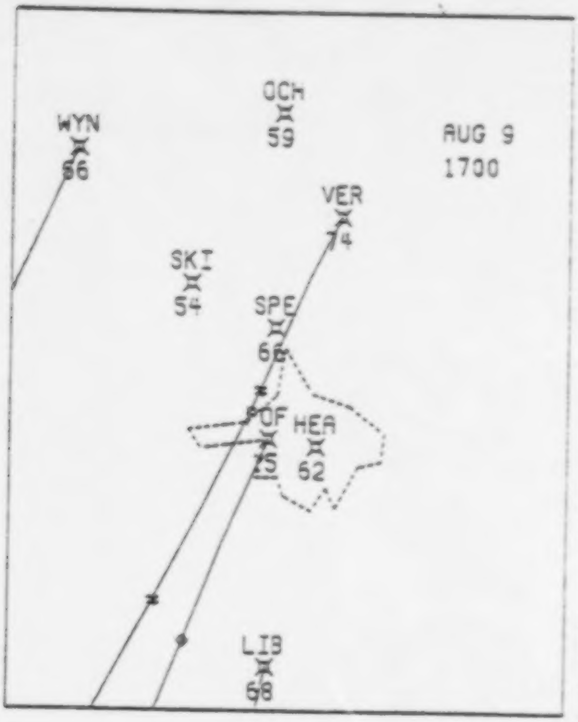
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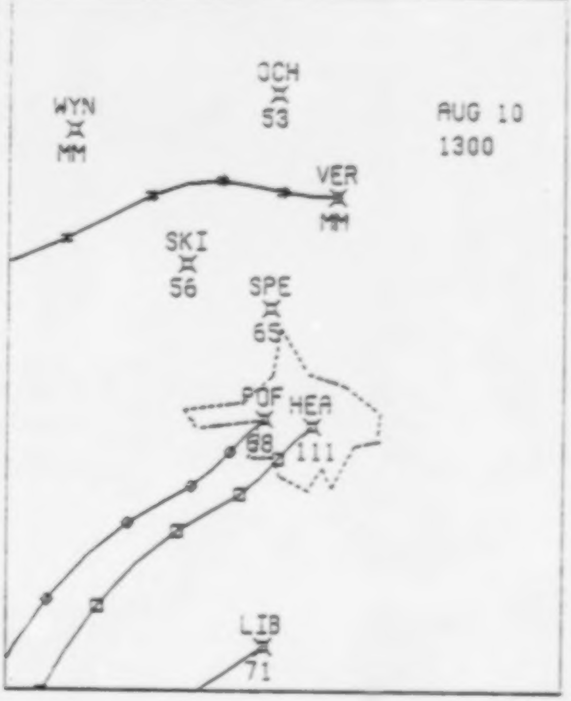
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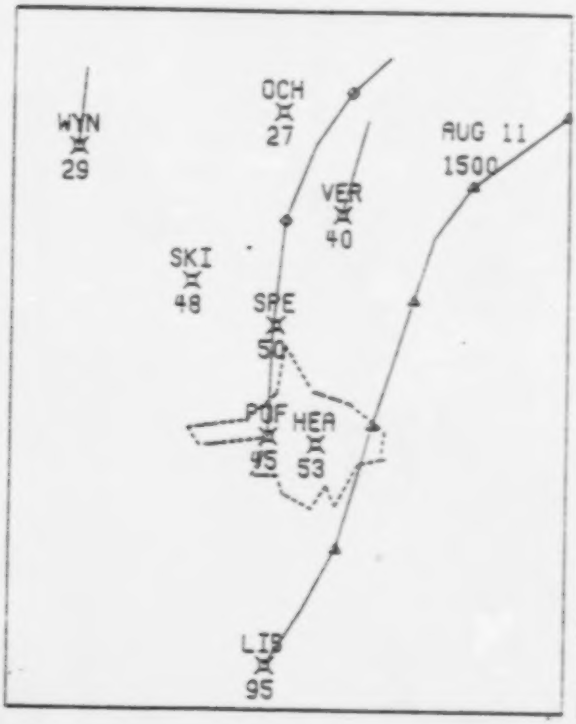
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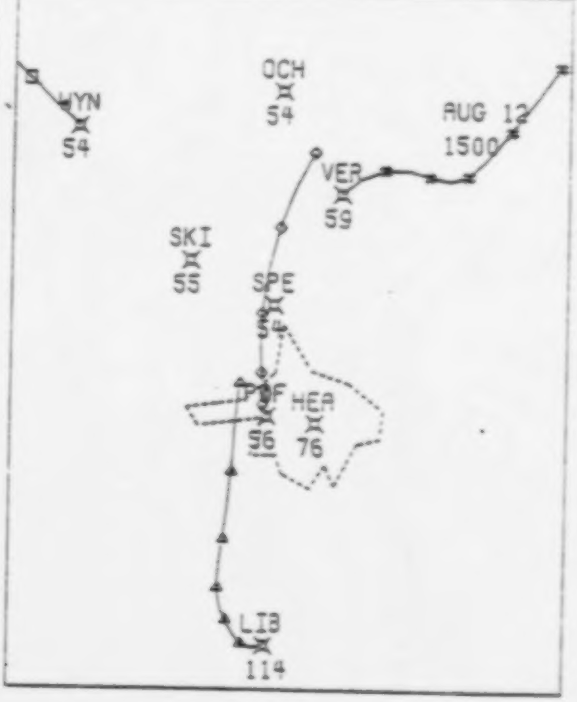
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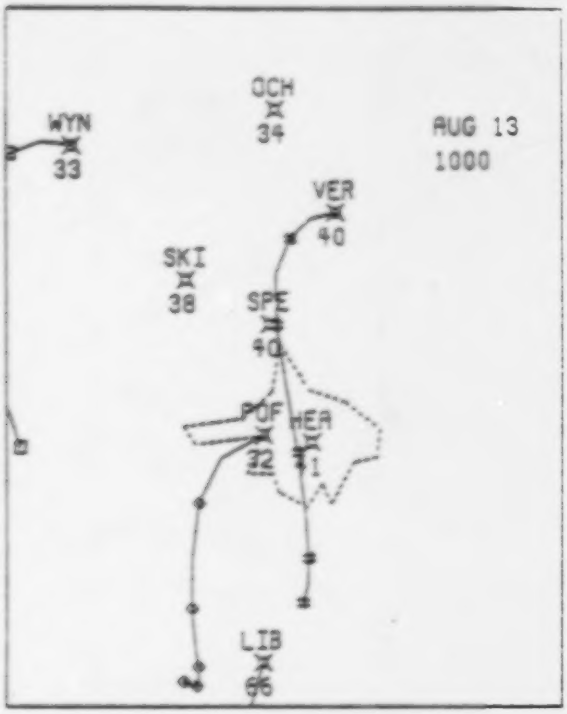
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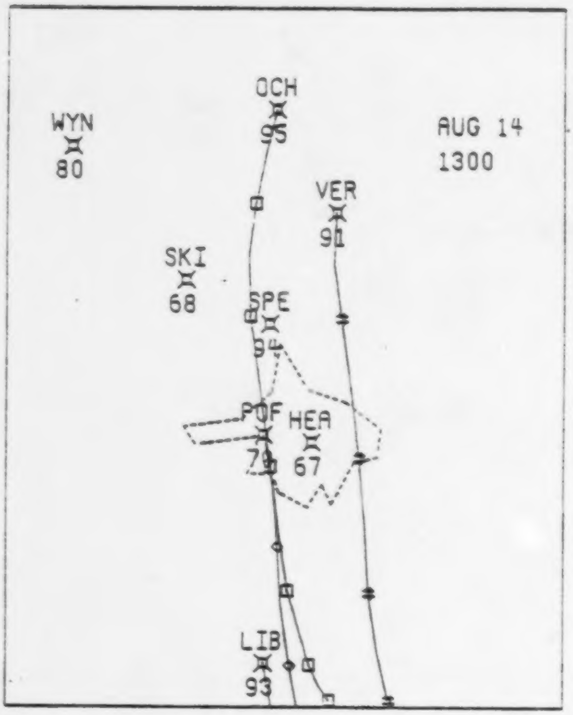
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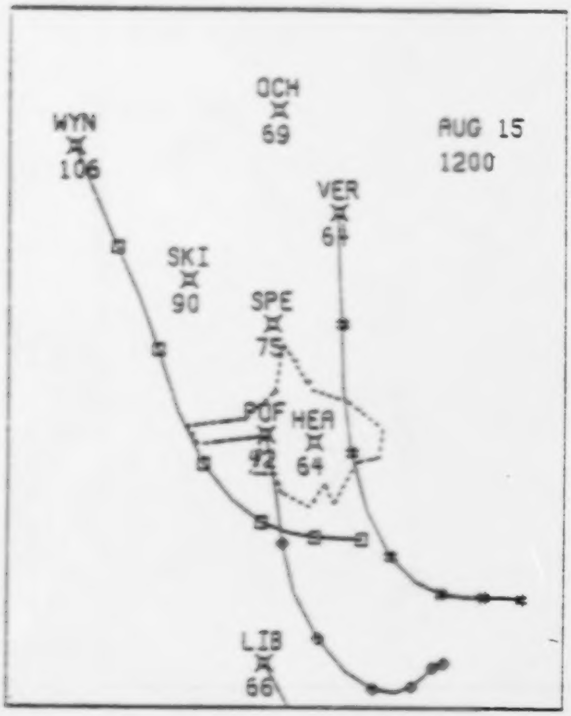
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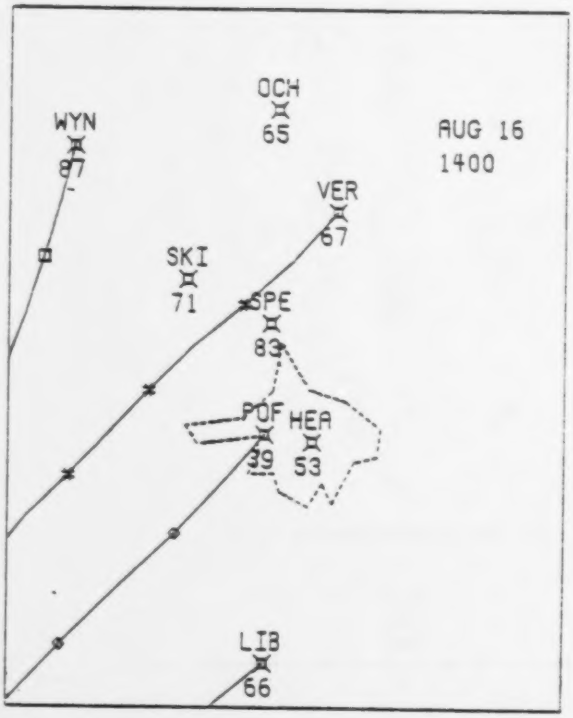
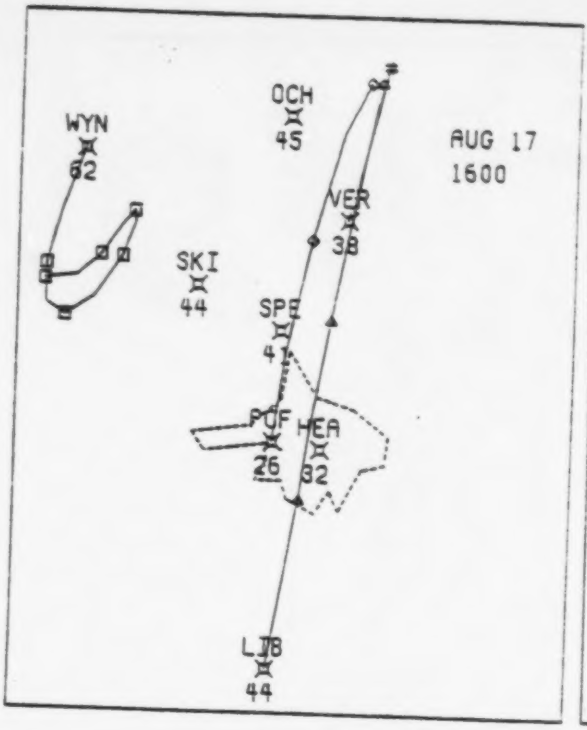

OCH
65
WYN
87
AUG 16
1400
VER
67
SKI
71
SPE
83
POF
39
HEA
53
LIB
66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OCH
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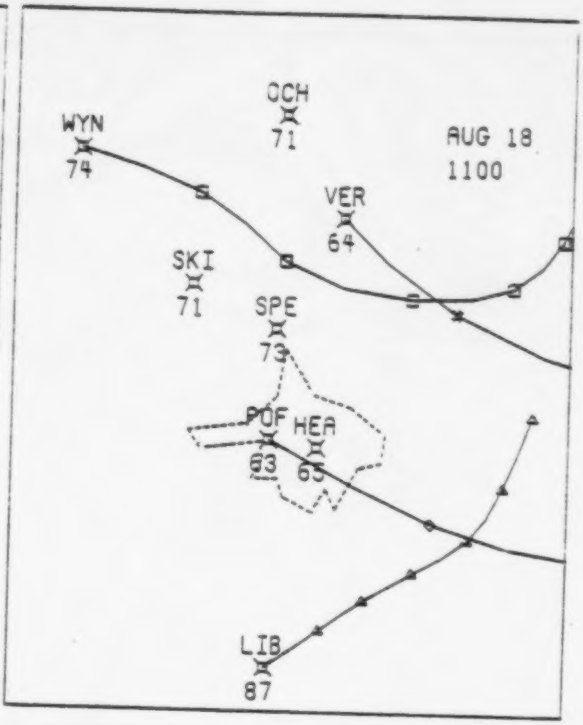
AUG 17
1600
VER
38
SKI
44
SPE
41
POF
26
HEA
32
LIB
44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OCH
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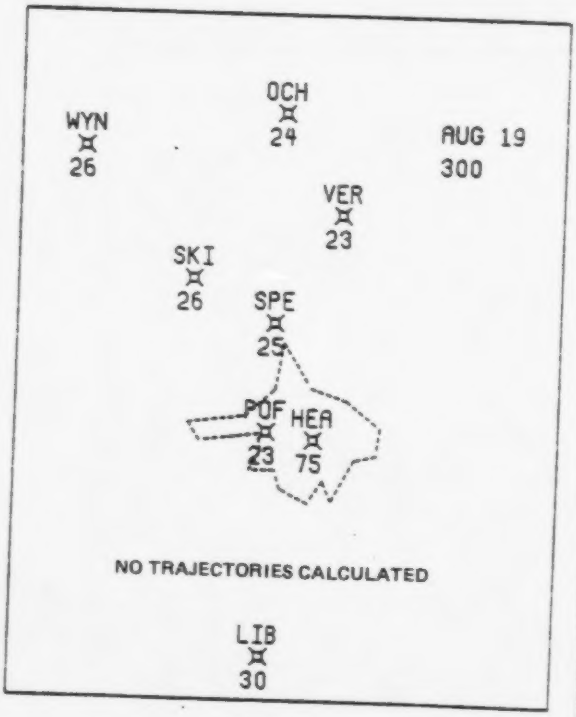
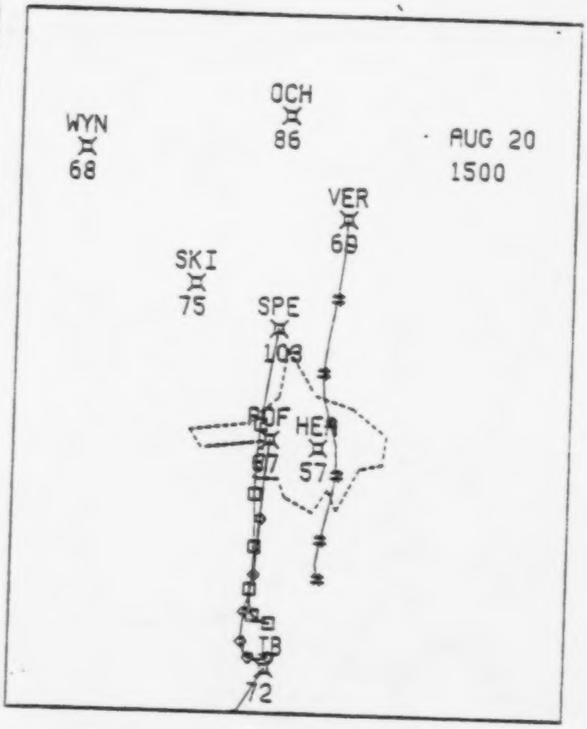
AUG 18
1100
VER
64
SKI
71
SPE
73
POF
63
HEA
65
LIB
87


WYN
26
OCH
24
AUG 19
300
VER
23
SKI
26
SPE
25
POF
23
HEA
75
NO TRAJECTORIES CALCULATED
LIB
30


WYN
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OCH
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VER
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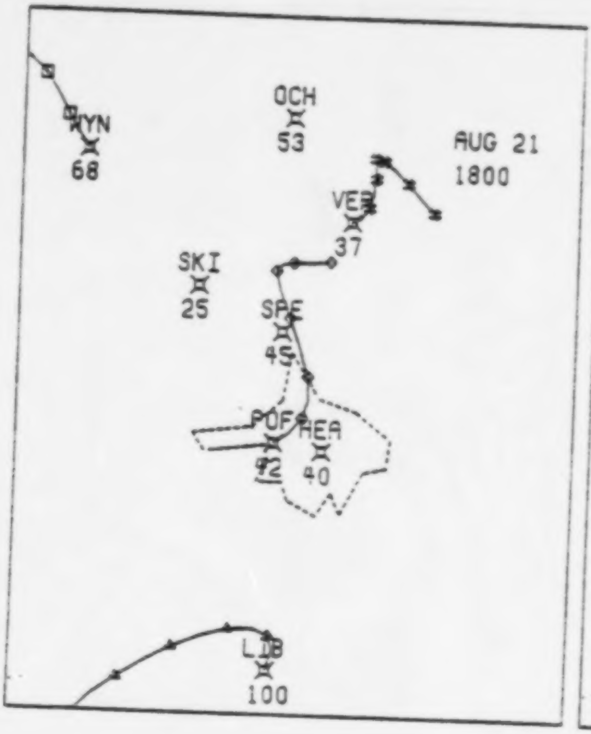
SKI
75
SPE
108
POF
87
HEA
57
LIB
72


WYN
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OCH
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AUG 21
1800
VER
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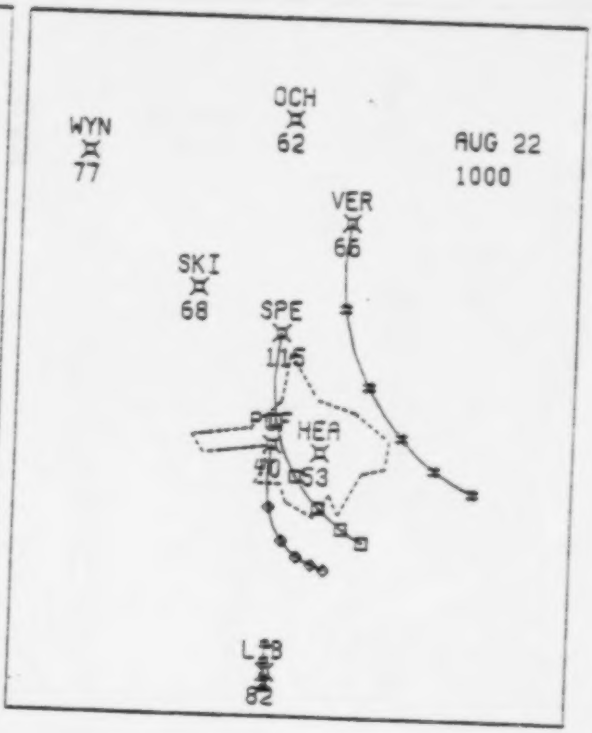
SKI
25
SPE
45
POF
92
HEA
40
LIB
100


WYN
77
OCH
62
AUG 22
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VER
66
SKI
68
SPE
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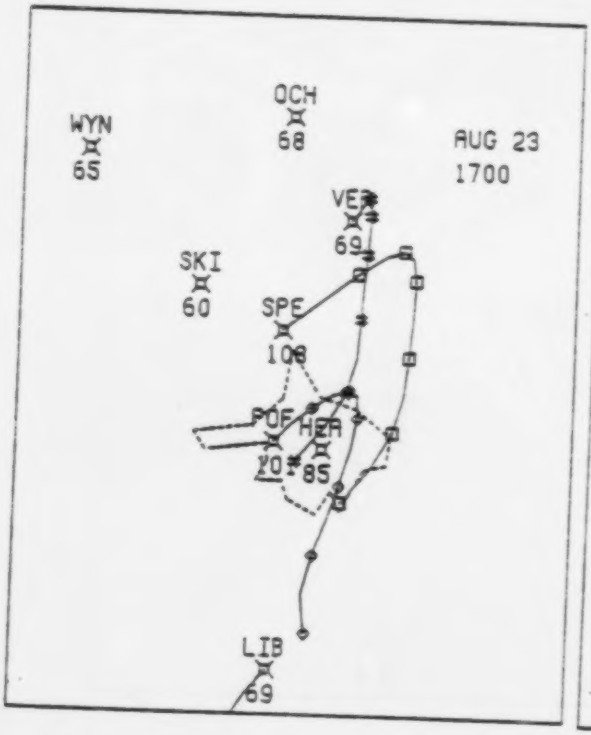
POF
90
HEA
53
LIB
82


WYN
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OCH
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AUG 23
1700
VER
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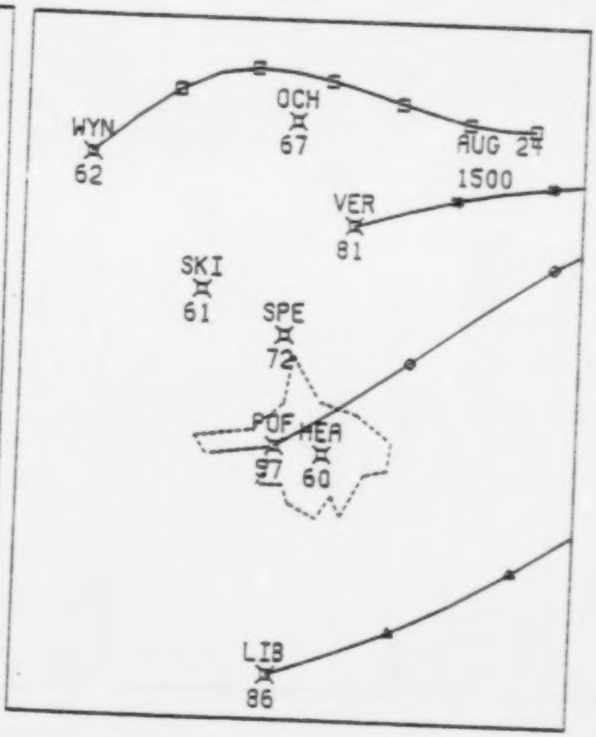
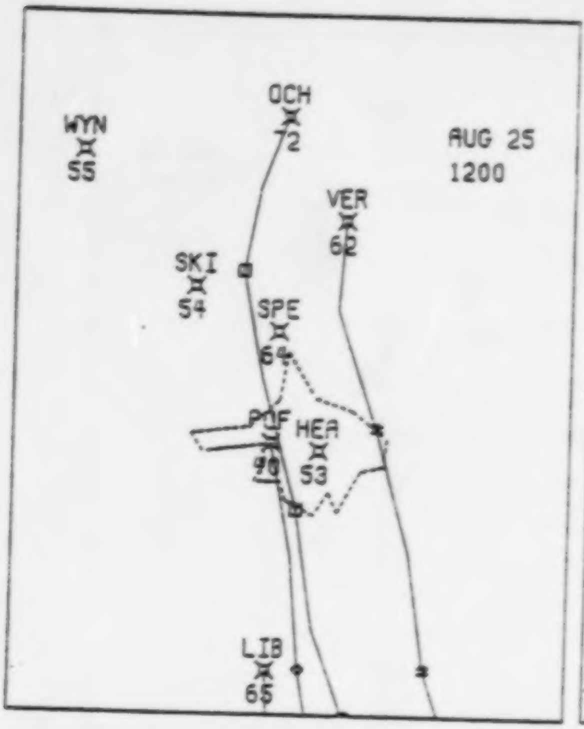
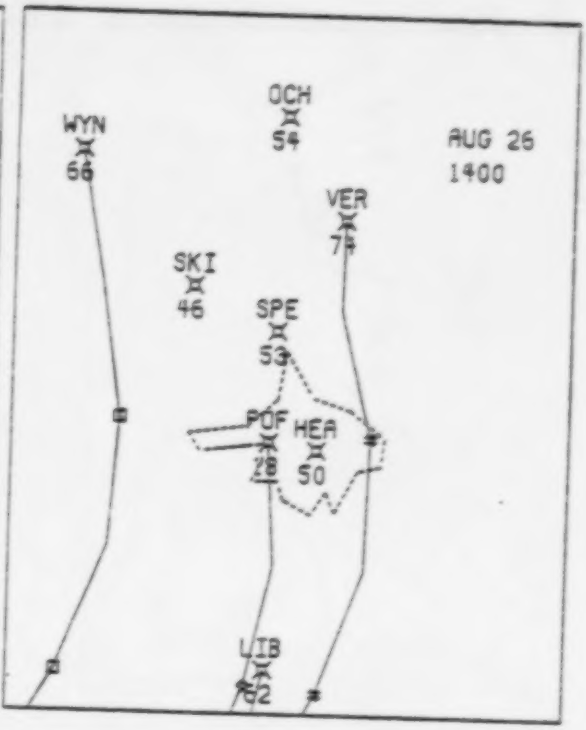
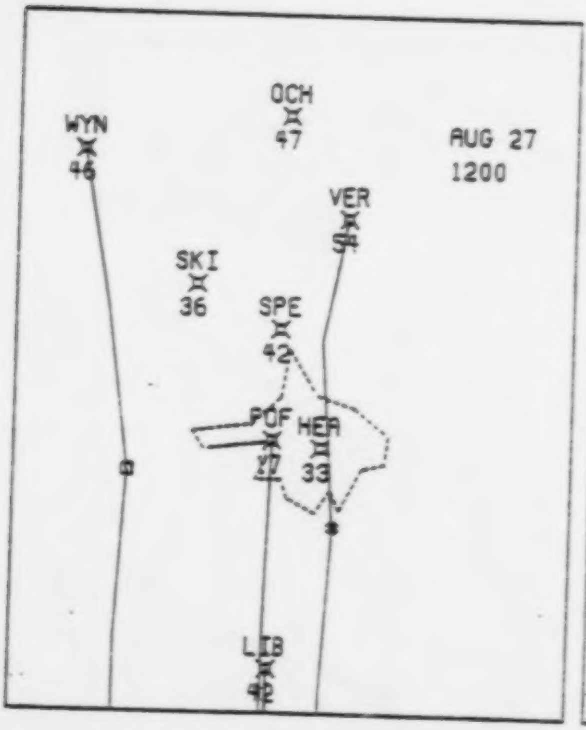
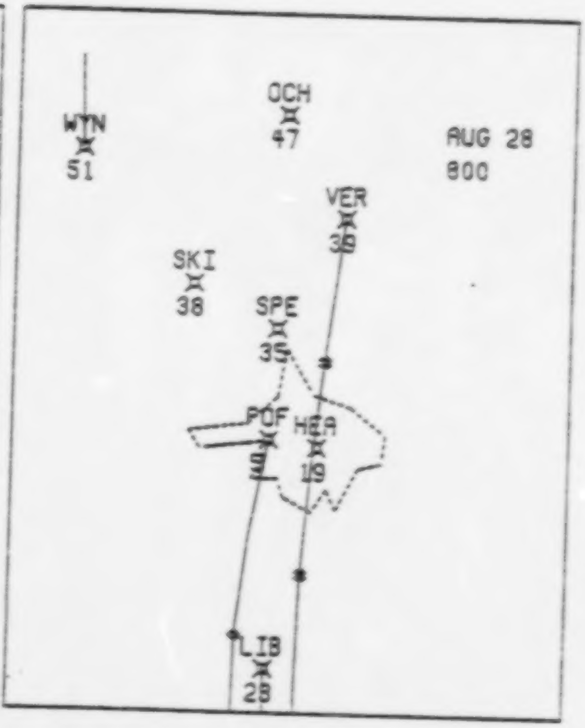
SKI
60
SPE
108
POF
101
HEA
85
LIB
69

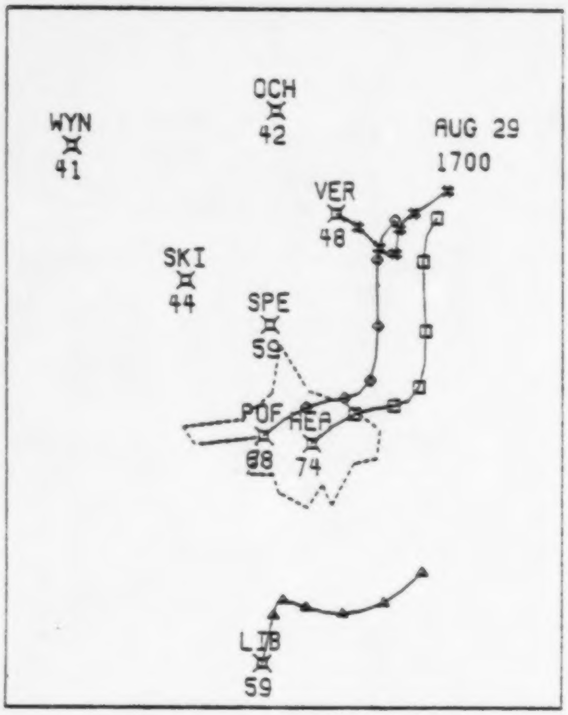

WYN
62
OCH
67
AUG 24
1500
VER
81
SKI
61
SPE
72
POF
97
HEA
60
LIB
86

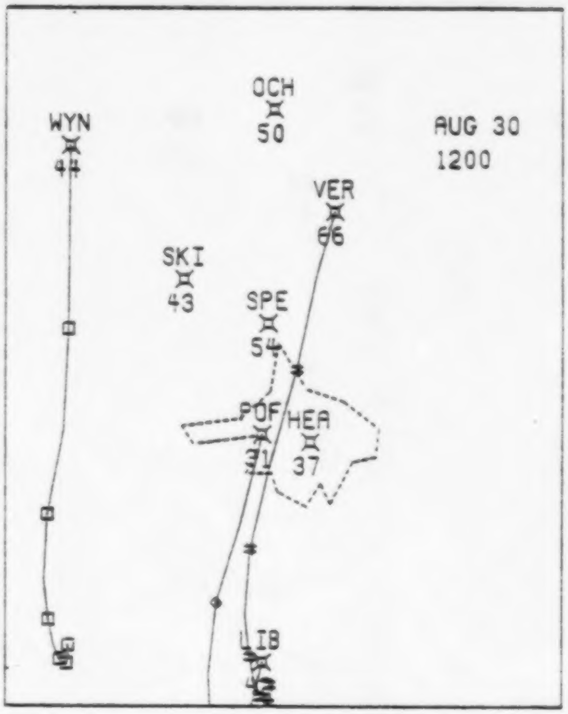

WYN
55
OCH
72
AUG 25
1200
VER
62
SKI
54
SPE
64
POF
90
HEA
53
LIB
65

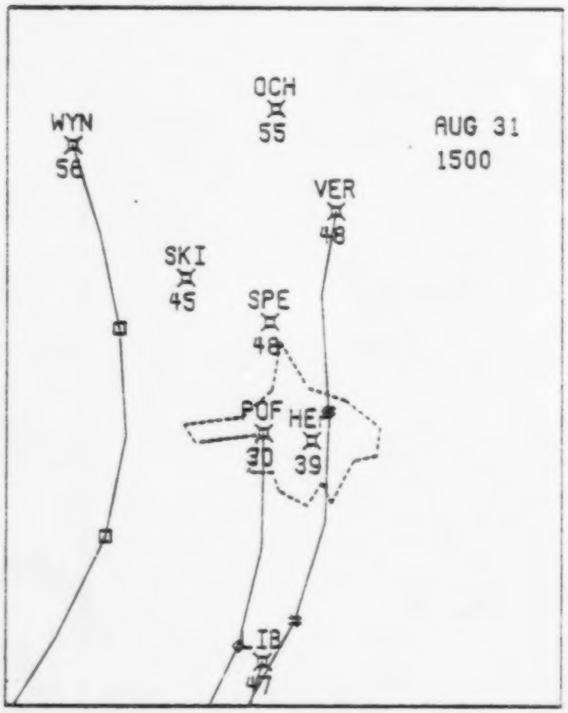

WYN
66
OCH
54
AUG 26
1400
VER
74
SKI
46
SPE
53
POF
78
HEA
50
LIB
62

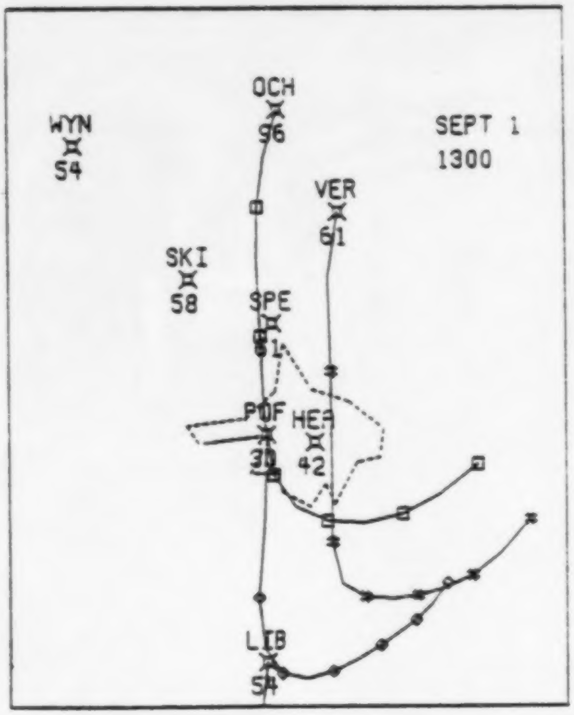

WYN
46
OCH
47
AUG 27
1200
VER
54
SKI
36
SPE
42
POF
47
HEA
33
LIB
42

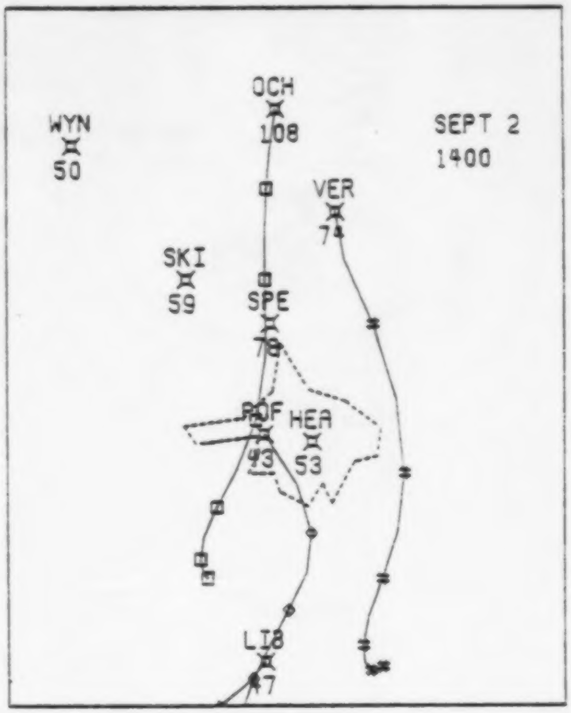

WYN
51
OCH
47
AUG 28
800
VER
39
SKI
38
SPE
35
POF
9
HEA
19
LIB
28

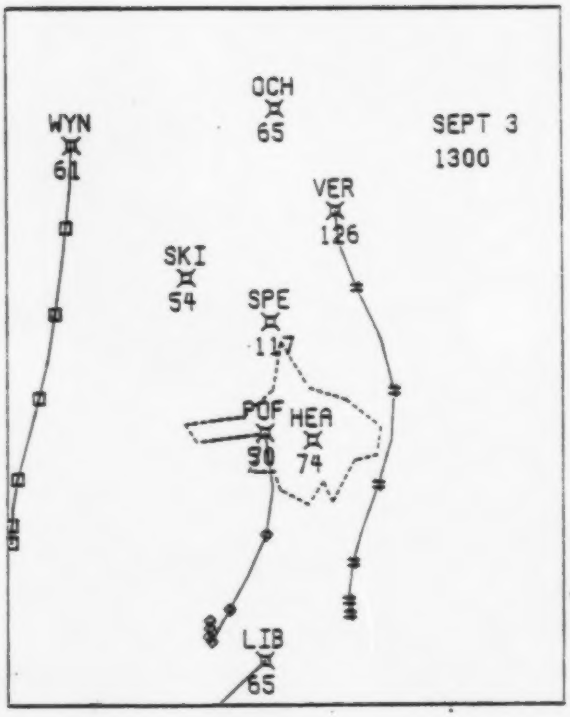

WYN
41
OCH
42
AUG 29
1700
VER
48
SKI
44
SPE
59
POF
68
HEA
74
LIB
59

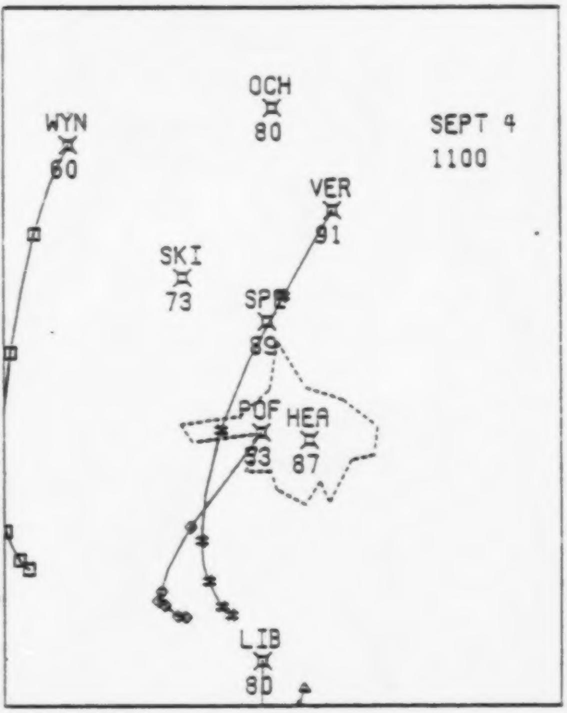

WYN
44
OCH
50
AUG 30
1200
VER
66
SKI
43
SPE
54
POF
31
HEA
37
LIB
42


WYN
56
OCH
55
AUG 31
1500
VER
48
SKI
45
SPE
48
POF
30
HEA
39
LIB
47


WYN
54
OCH
96
SEPT 1
1300
VER
61
SKI
58
SPE
61
POF
30
HEA
42
LIB
54


WYN
50
OCH
108
SEPT 2
1400
VER
74
SKI
59
SPE
70
POF
43
HEA
53
LIB
47


OCH
65
WYN
61
SEPT 3
1300
VER
126
SKI
54
SPE
117
POF
90
HEA
74
LIB
65


OCH
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WYN
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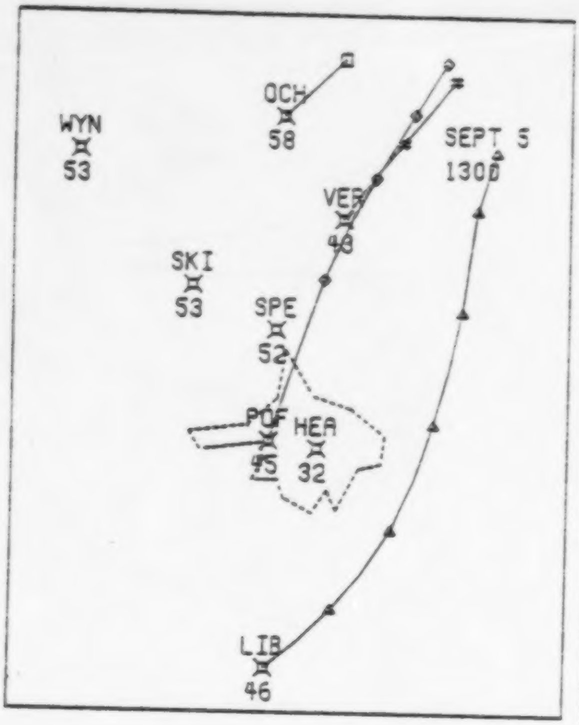
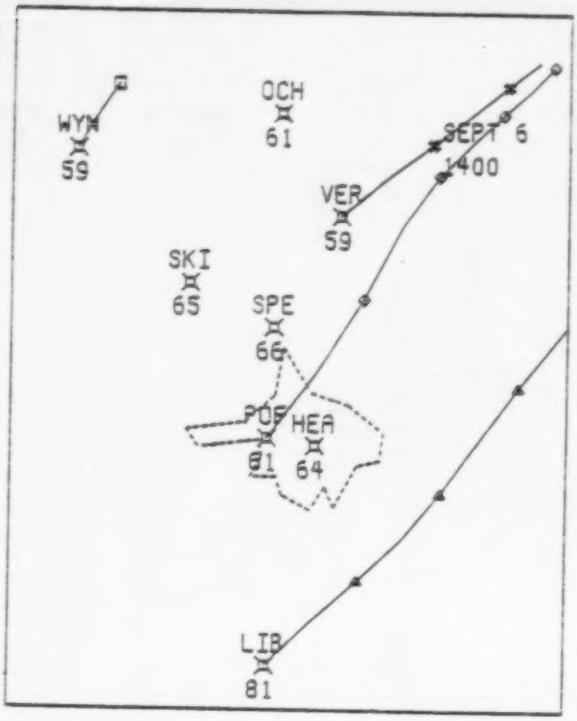
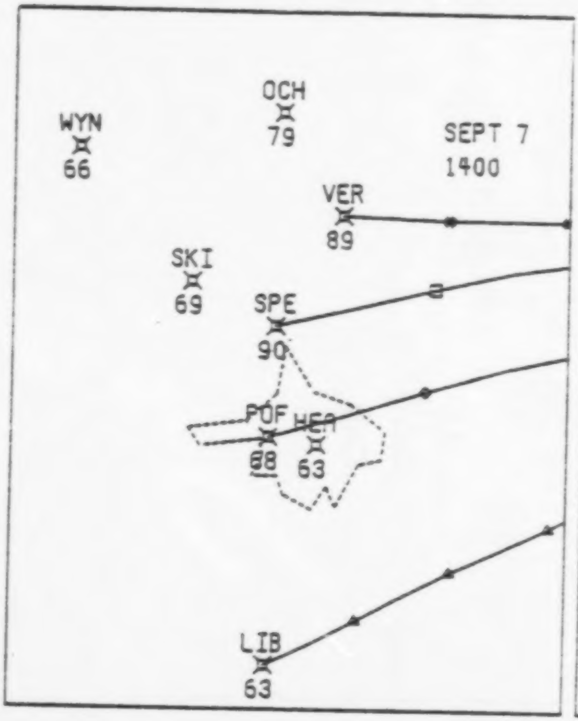
SEPT 4
1100
VER
91
SKI
73
SPE
89
POF
93
HEA
87
LIB
80


WYN
53
OCH
58
SEPT 5
1300
VER
48
SKI
53
SPE
52
POF
45
HEA
32
LIB
46


WYN
59
OCH
61
SEPT 6
1400
VER
59
SKI
65
SPE
66
POF
81
HEA
64
LIB
81


WYN
66
OCH
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SEPT 7
1400
VER
89
SKI
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SPE
90
POF
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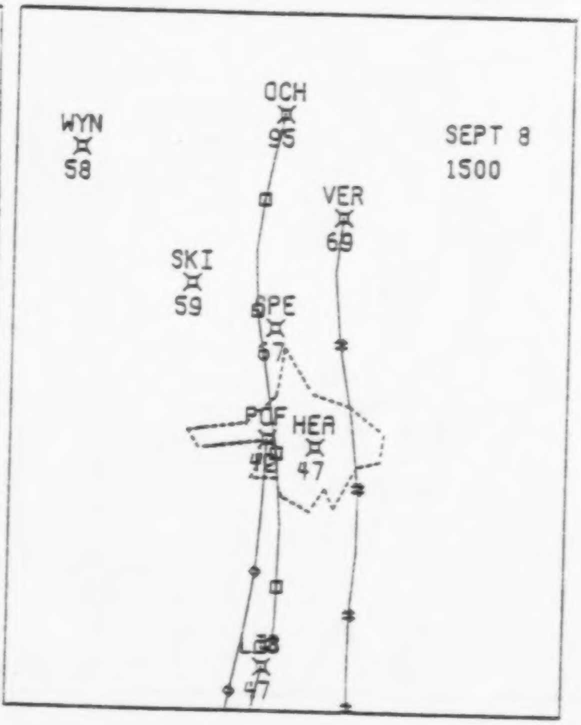
HEA
63
LIB
63


WYN
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OCH
95
SEPT 8
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VER
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SKI
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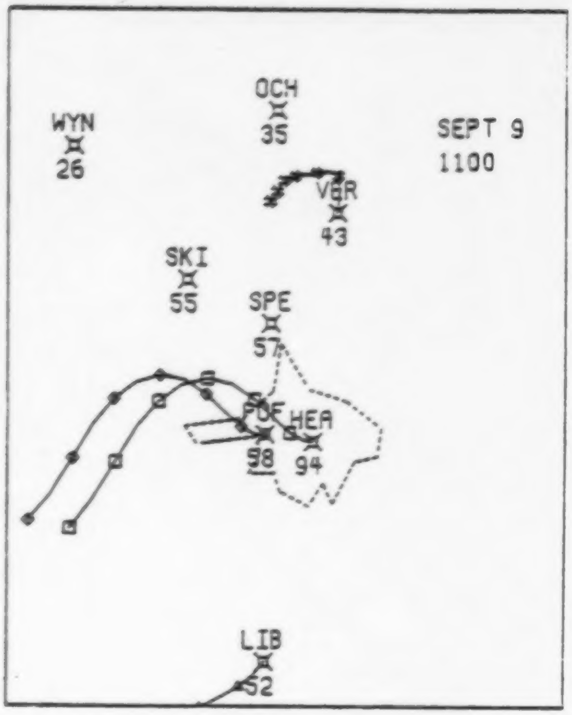
SPE
67
POF
HEA
47
LIB
47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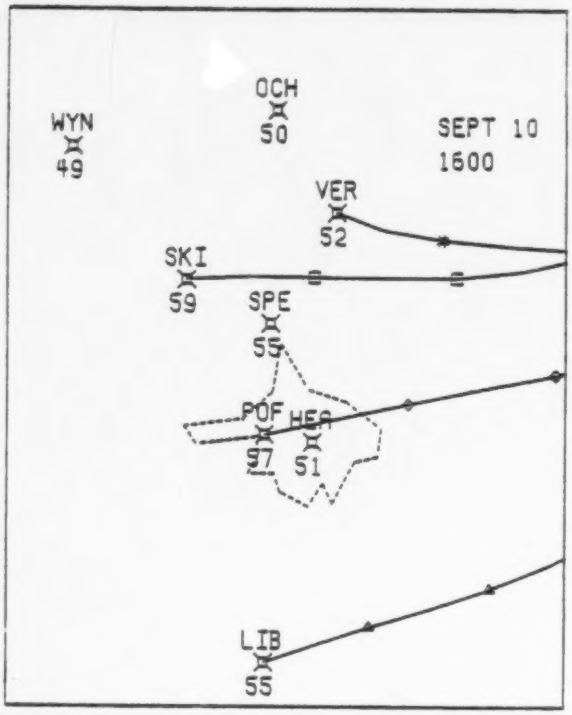
26
OCH
35
SEPT 9
1100
VER
43
SKI
55
SPE
57
POF
98
HEA
94
LIB
52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OCH
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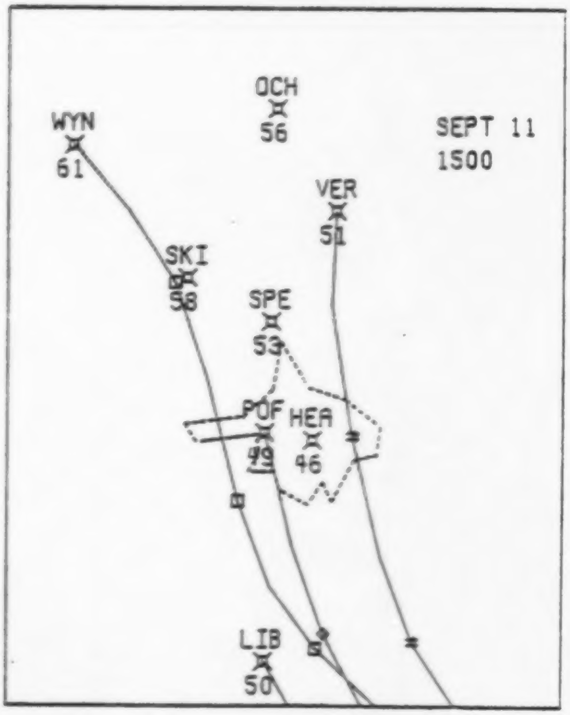
SEPT 10
1600
VER
52
SKI
59
SPE
55
POF
97
HEA
51
LIB
55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61
OCH
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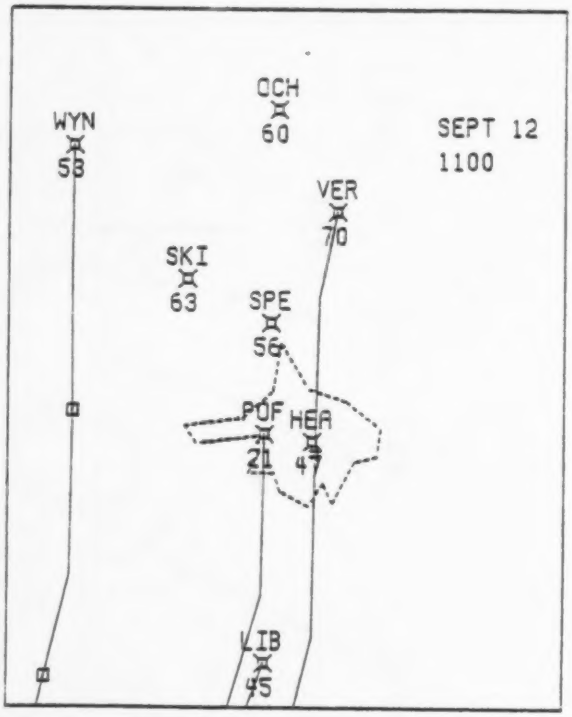
SEPT 11
1500
VER
51
SKI
58
SPE
53
POF
49
HEA
46
LIB
50


WYN
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OCH
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SEPT 12
1100
VER
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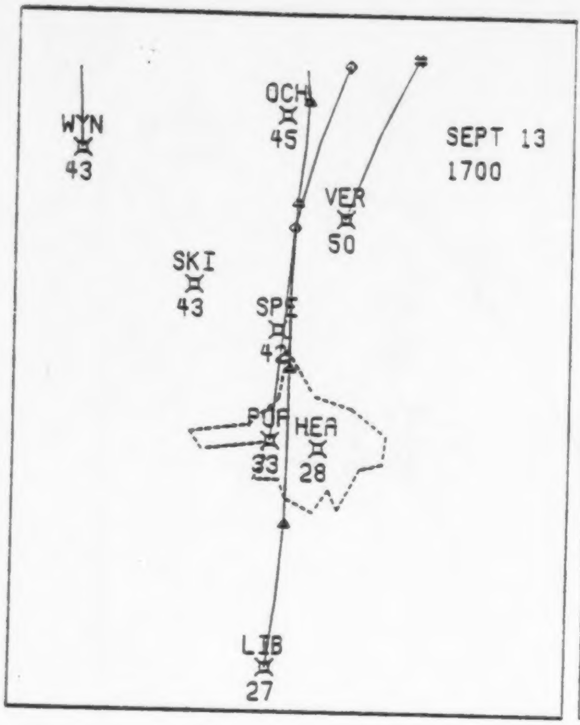
SKI
63
SPE
56
POF
21
HEA
47
LIB
45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43
OCH
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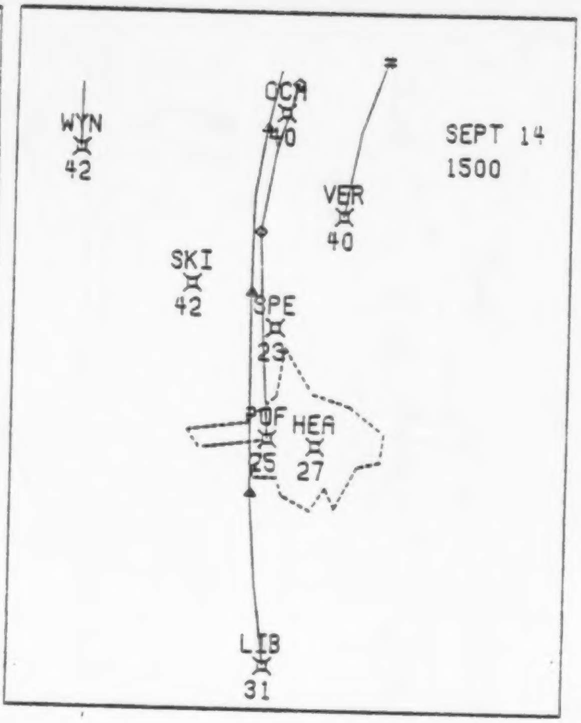
SEPT 13
1700
VER
50
SKI
43
SPE
42
POF
33
HEA
28
LIB
27


WYN
42
OCH
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SEPT 14
1500
VER
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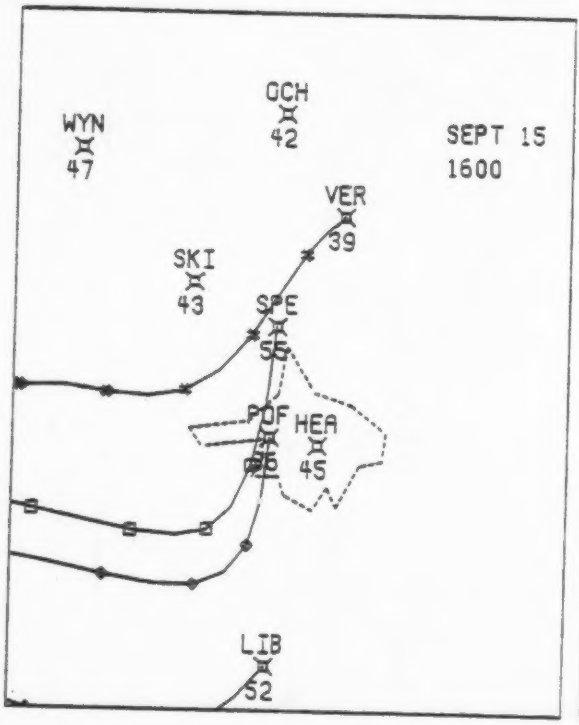
SKI
42
SPE
23
POF
25
HEA
27
LIB
31


WYN
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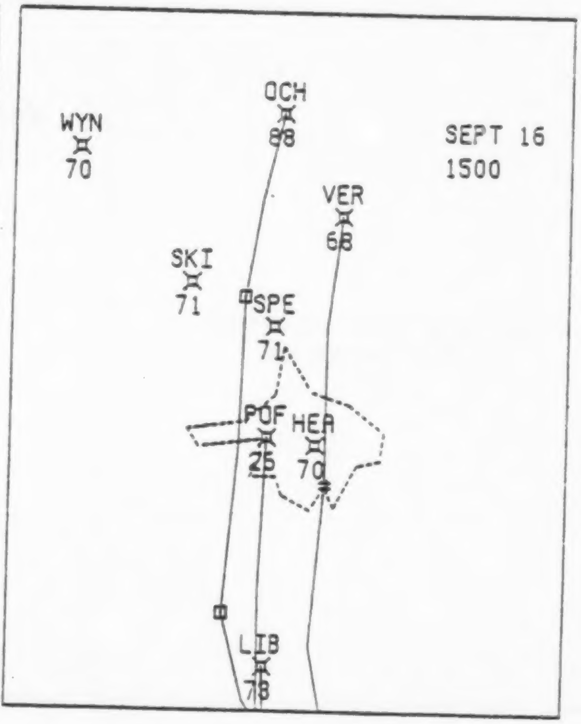
OCH
42
SEPT 15
1600
VER
39
SKI
43
SPE
55
POF
36
HEA
45
LIB
52


WYN
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OCH
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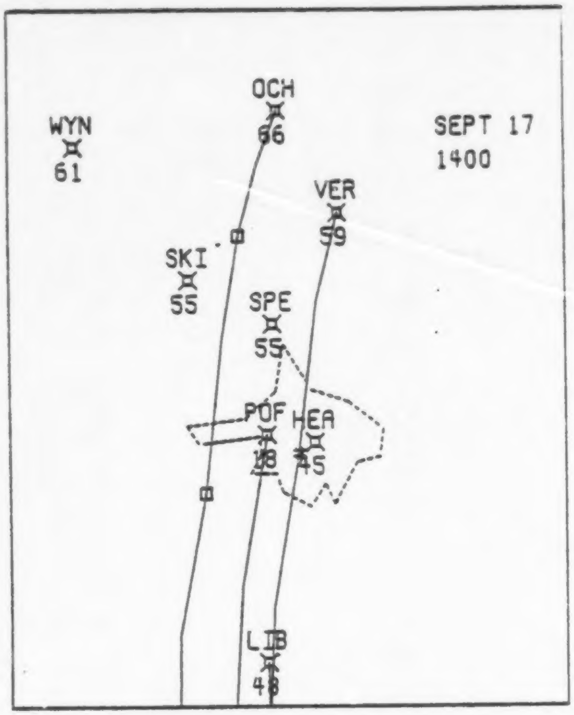
SEPT 16
1500
VER
68
SKI
71
SPE
71
POF
25
HEA
70
LIB
78


OCH
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WYN
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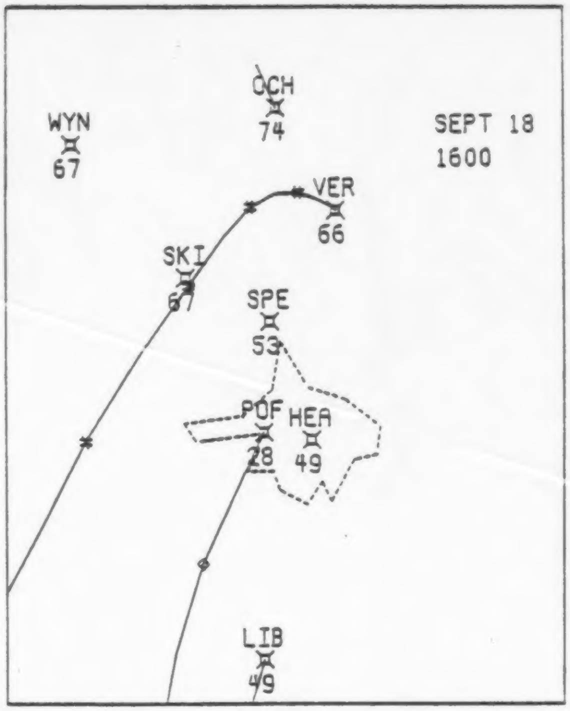
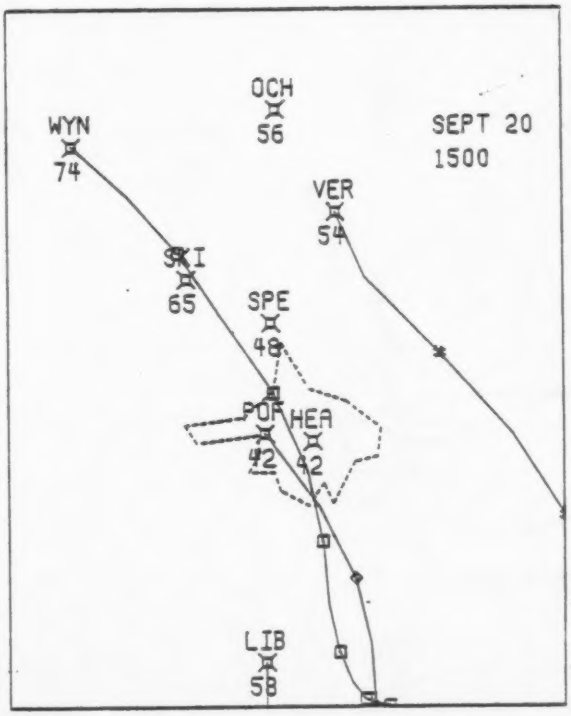
SEPT 17
1400
VER
59
SKI
55
SPE
55
POF
18
HEA
45
LIB
48


OCH
74
WYN
67
SEPT 18
1600
VER
66
SKI
67
SPE
53
POF
28
HEA
49
LIB
49

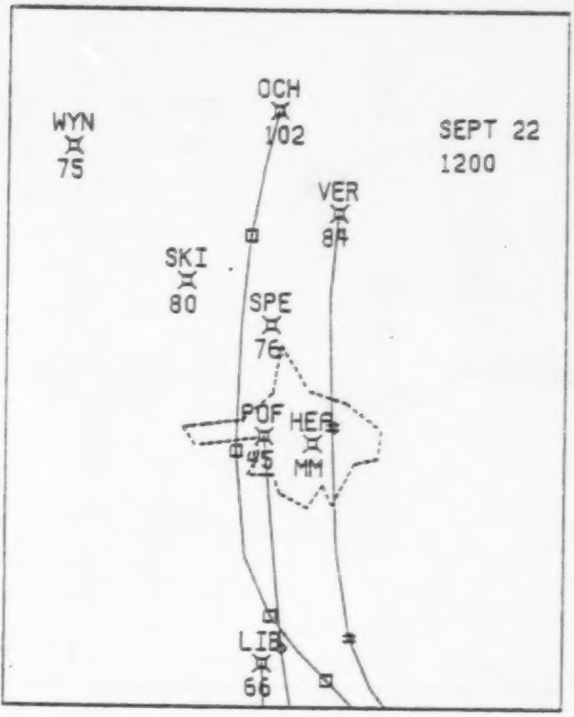
SEPT 19

NO TRAJECTORIES CALCULATED
DATA SET INCOMPLETE


OCH
56
WYN
74
SEPT 20
1500
VER
54
SKI
65
SPE
48
POF
42
HEA
42
LIB
58

SEPT 21

NO TRAJECTORIES CALCULATED
DATA SET INCOMPLETE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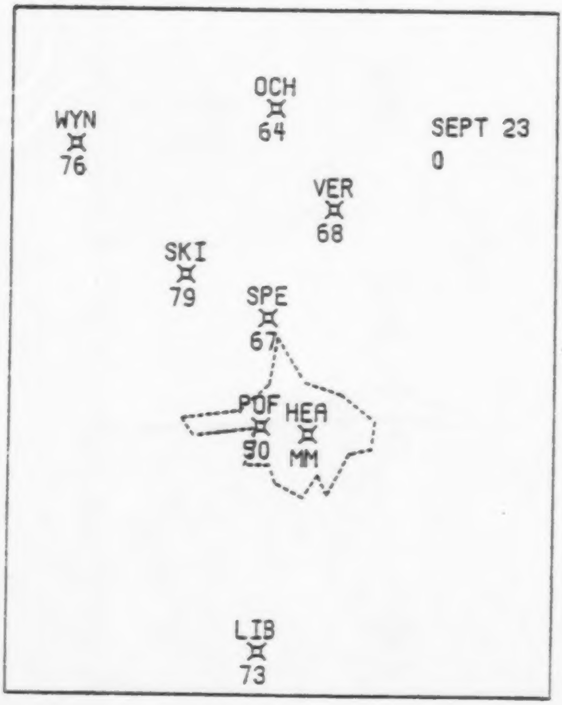
102
WYN
75
SEPT 22
1200
VER
84
SKI
80
SPE
76
POF
45
HEA
MM
LIB
66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76
OCH
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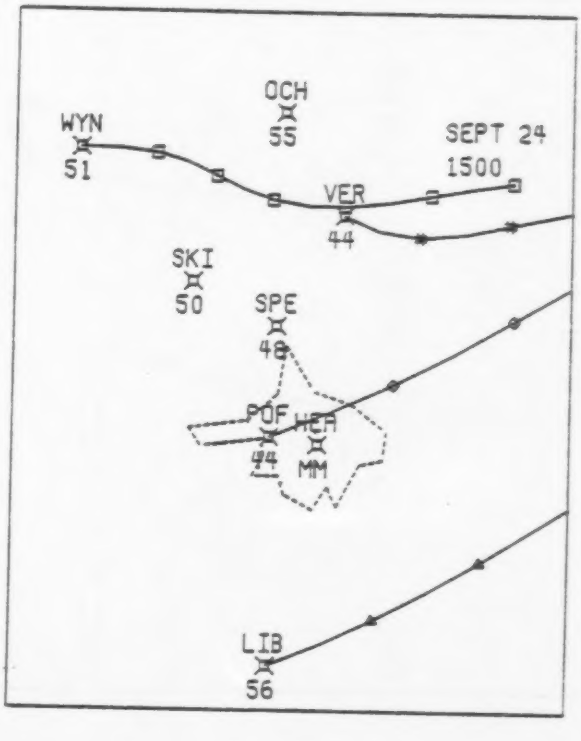
SEPT 23
0
VER
68
SKI
79
SPE
67
POF
50
HEA
MM
LIB
73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OCH
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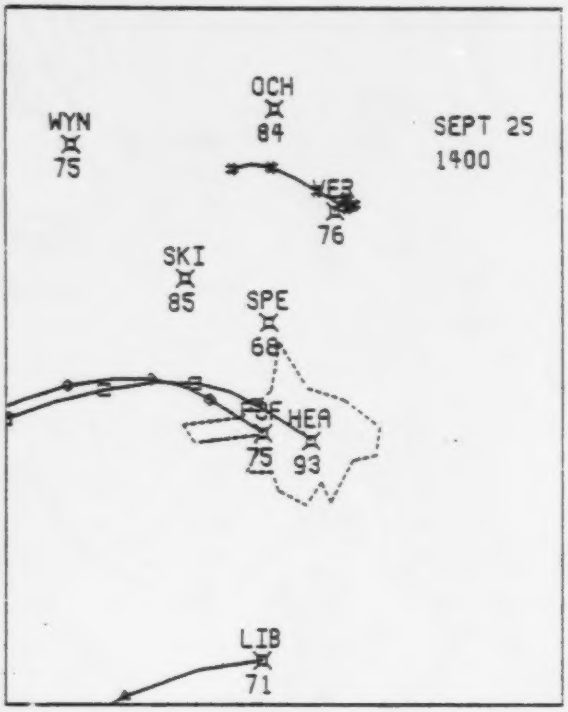
SEPT 24
1500
VER
44
SKI
50
SPE
48
POF
44
HEA
MM
LIB
56


OCH
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WYN
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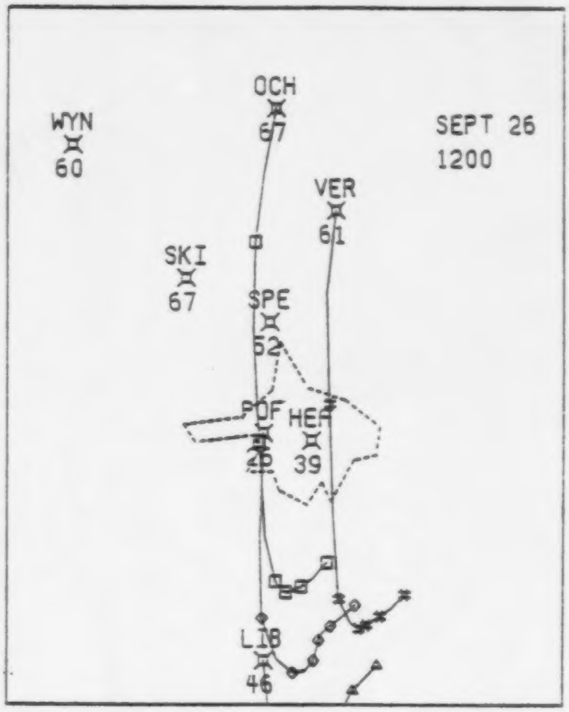
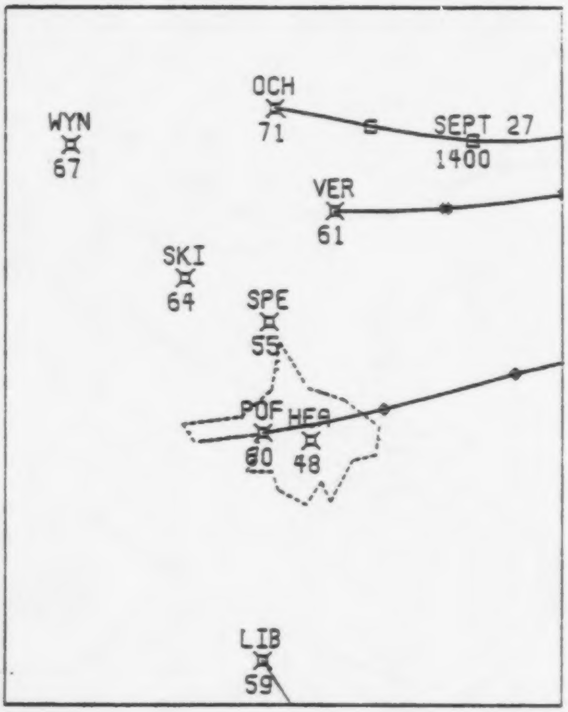
SEPT 25
1400
VER
76
SKI
85
SPE
68
POF
75
HEA
93
LIB
71


OCH
67
WYN
60
SEPT 26
1200
VER
61
SKI
67
SPE
52
POF
25
HEA
39
LIB
46


OCH
71
WYN
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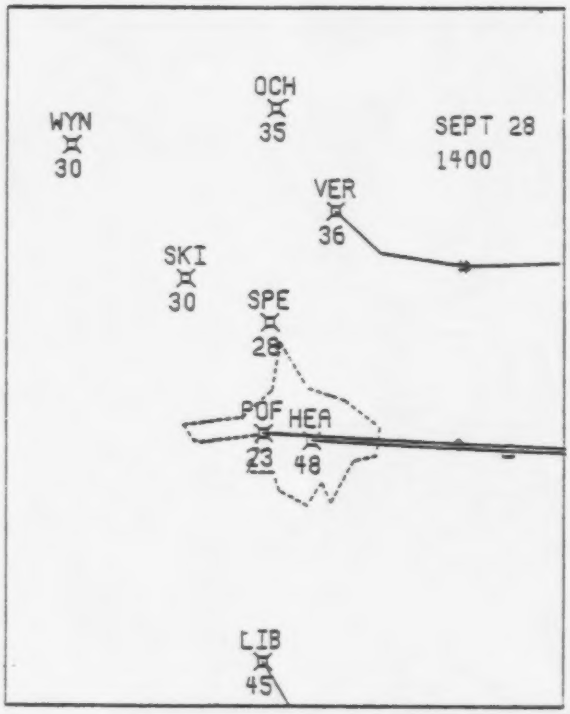
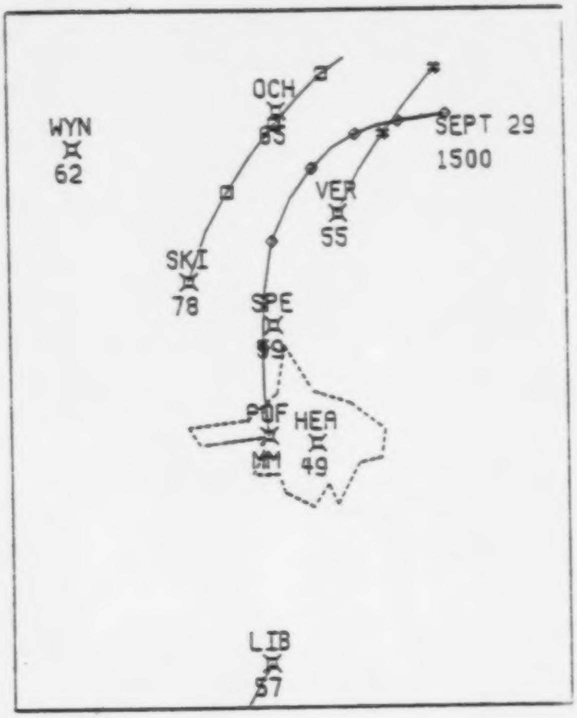
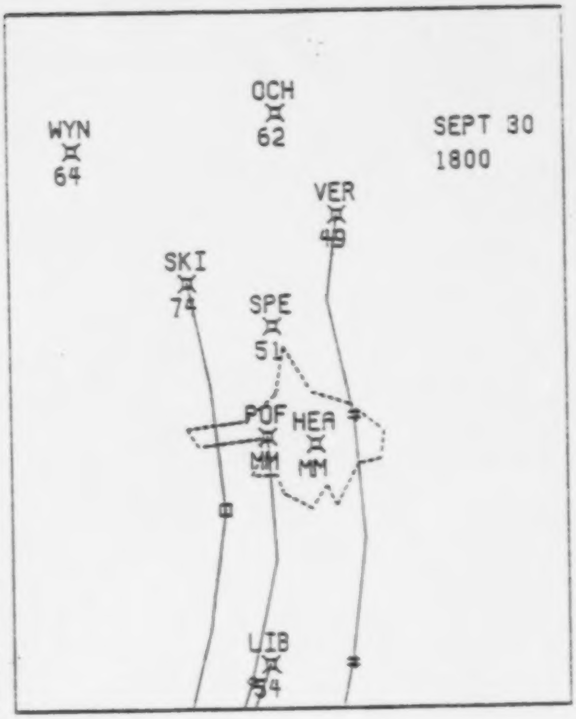
SEPT 27
1400
VER
61
SKI
64
SPE
55
POF
60
HEA
48
LIB
59

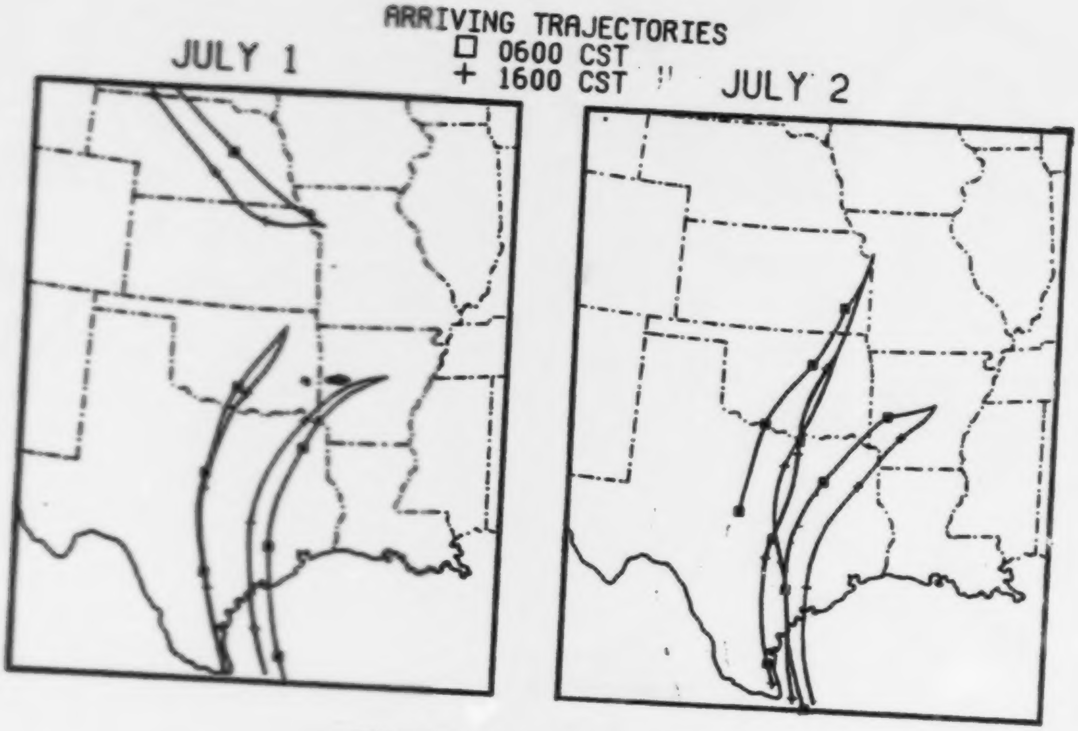

OCH
35
WYN
30
SEPT 28
1400
VER
36
SKI
30
SPE
28
POF
23
HEA
48
LIB
45


WYN
62
OCH
63
SEPT 29
1500
VER
55
SKI
78
SPE
59
POF
MM
HEA
49
LIB
57


WYN
64
OCH
62
SEPT 30
1800
VER
49
SKI
74
SPE
51
POF
MM
HEA
MM
LIB
54

# APPENDIX B

# SYNOPTIC SCALE AIR PARCEL TRAJECTORIES

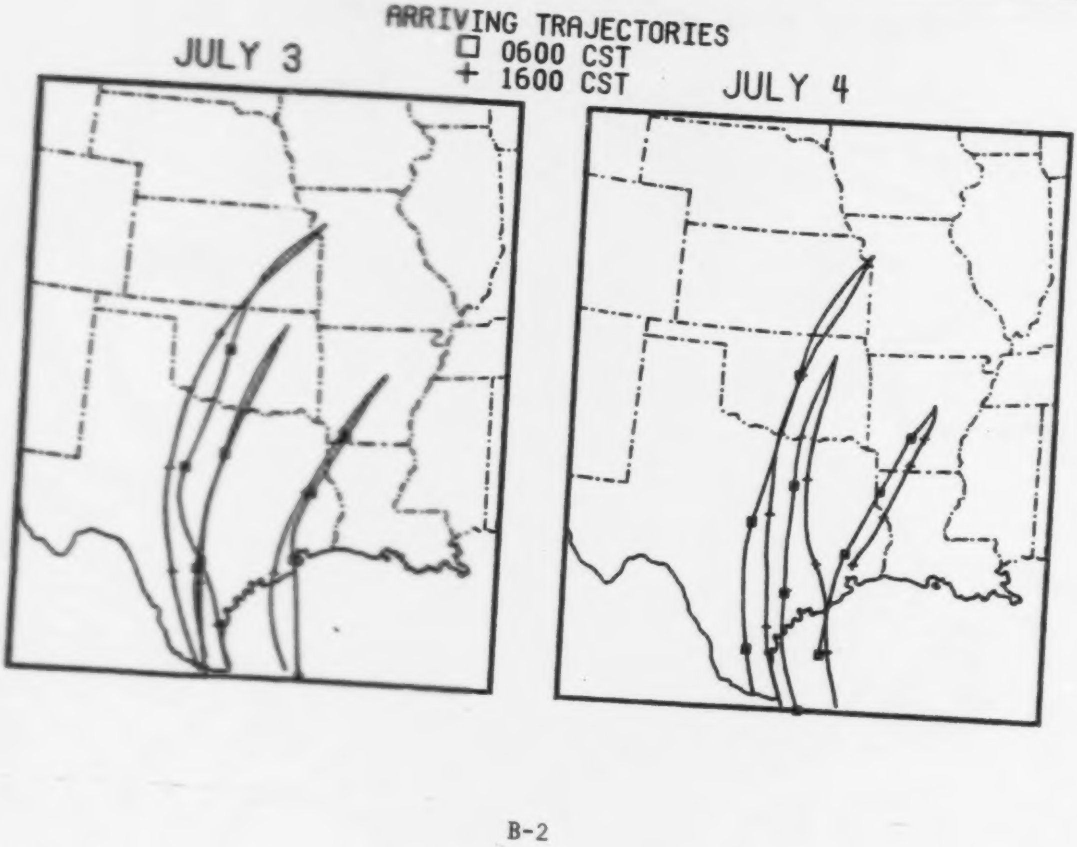


ARRIVING TRAJECTORIES

□ 0600 CST
+ 1600 CST

JULY 1

JULY 2



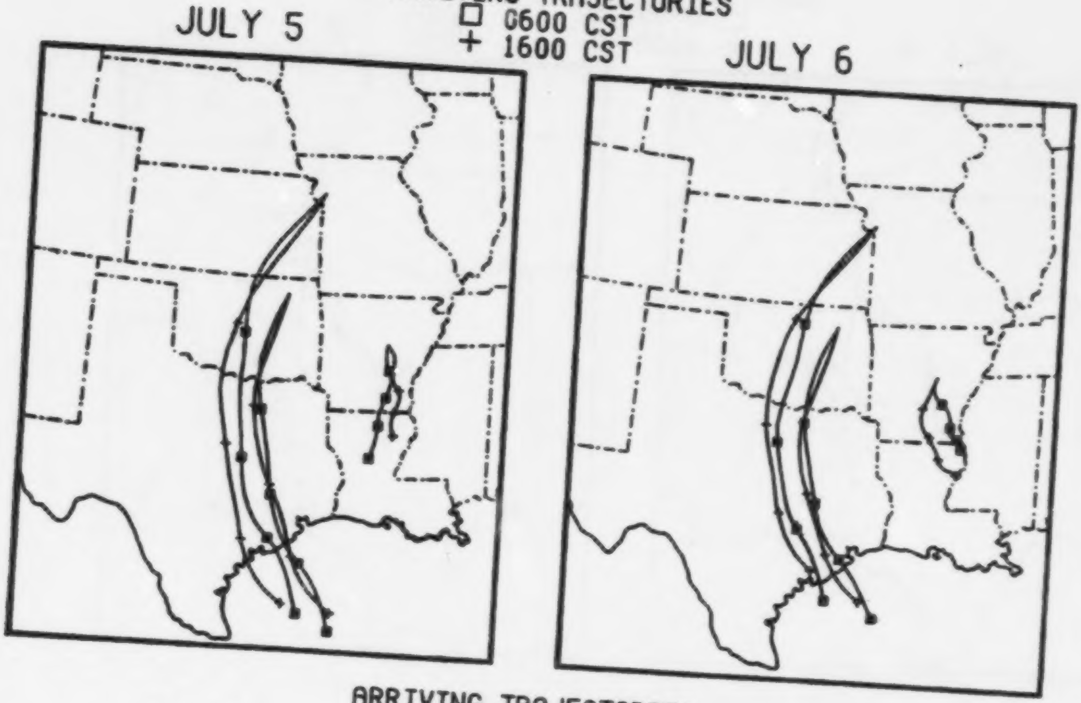
ARRIVING TRAJECTORIES

□ 0600 CST
+ 1600 CST

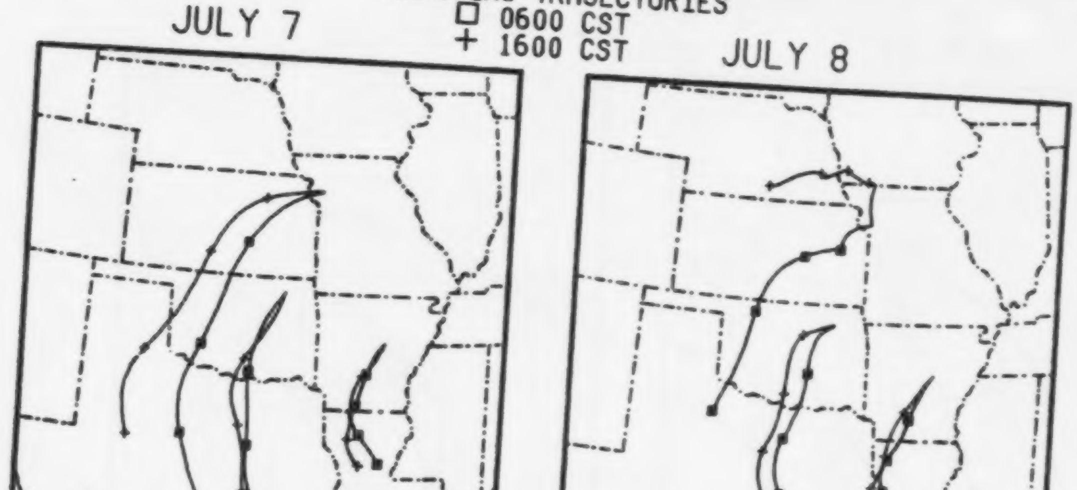
JULY 3

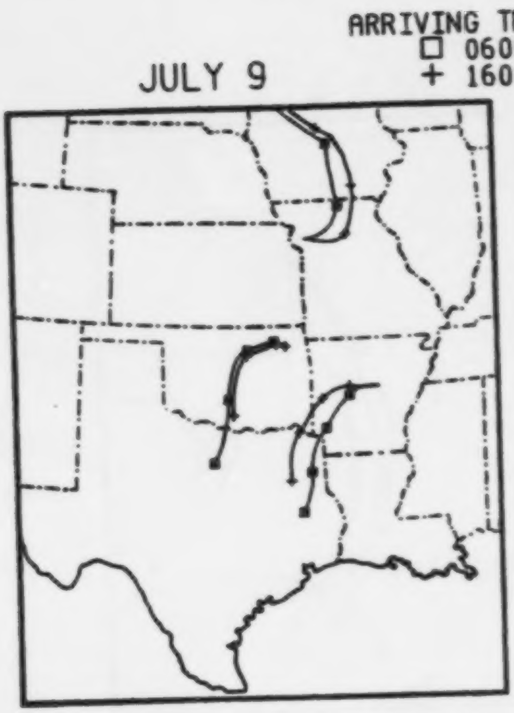
JULY 4

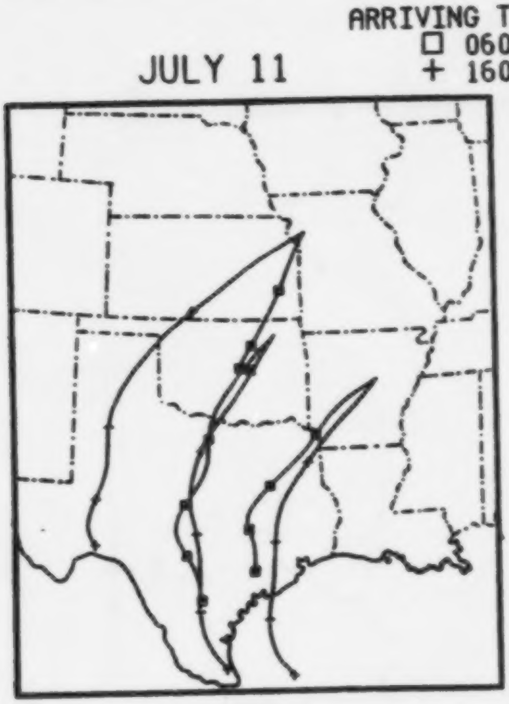
ARRIVING TRAJECTORIES

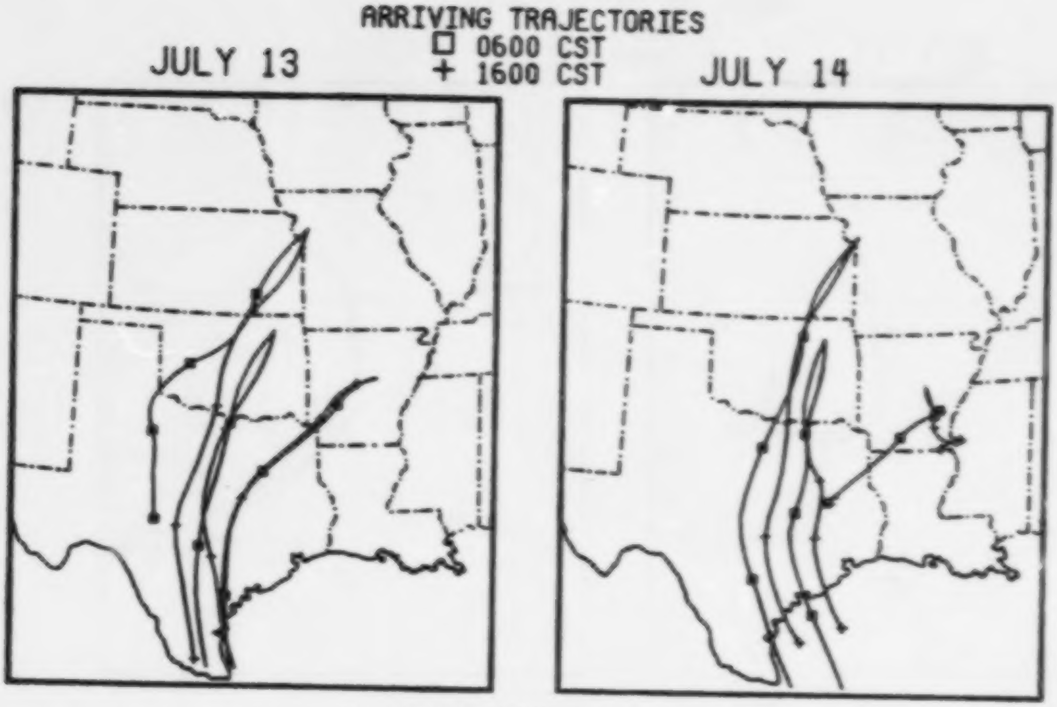

JULY 5
□ 0600 CST
+ 1600 CST
JULY 6

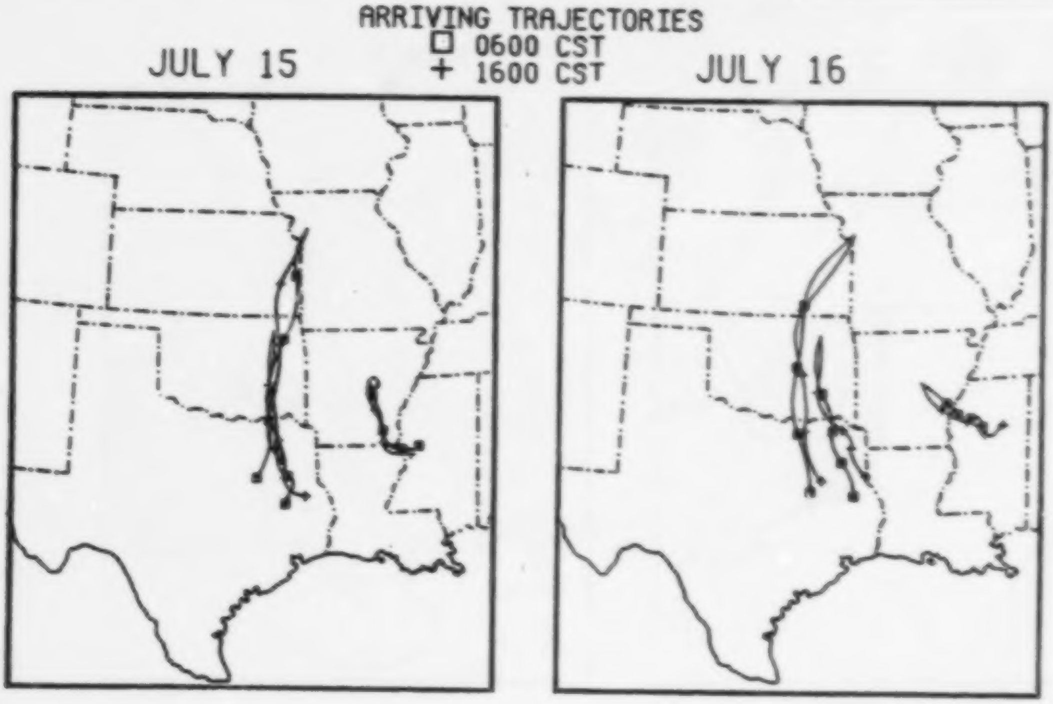
ARRIVING TRAJECTORIES

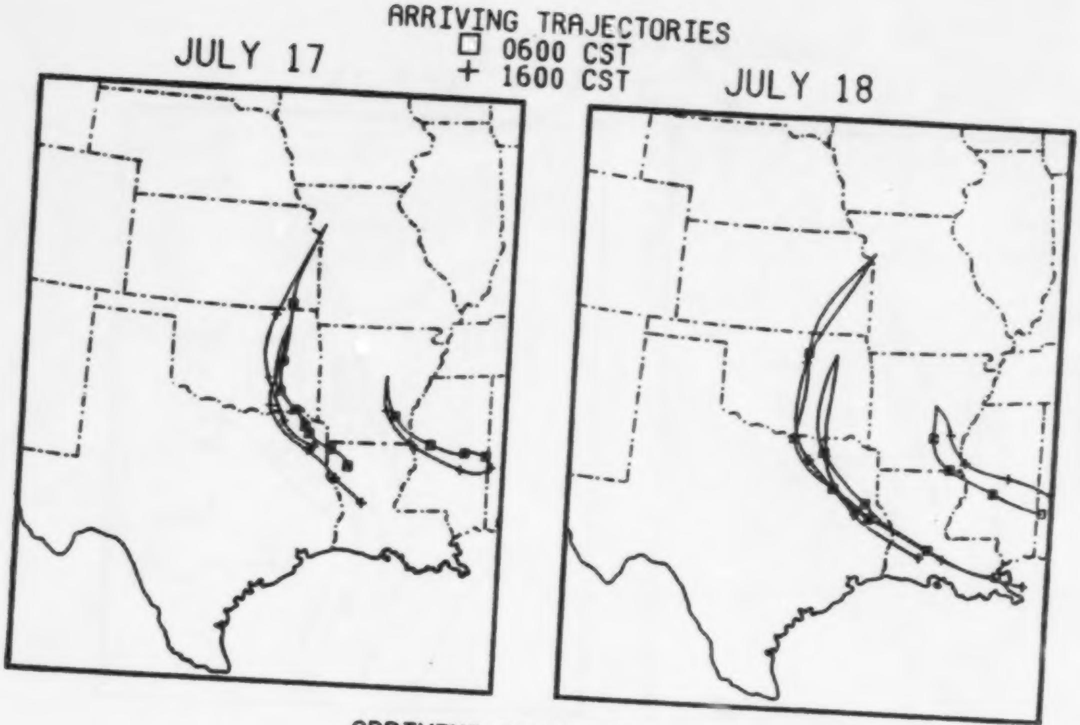

JULY 7
□ 0600 CST
+ 1600 CST
JULY 8

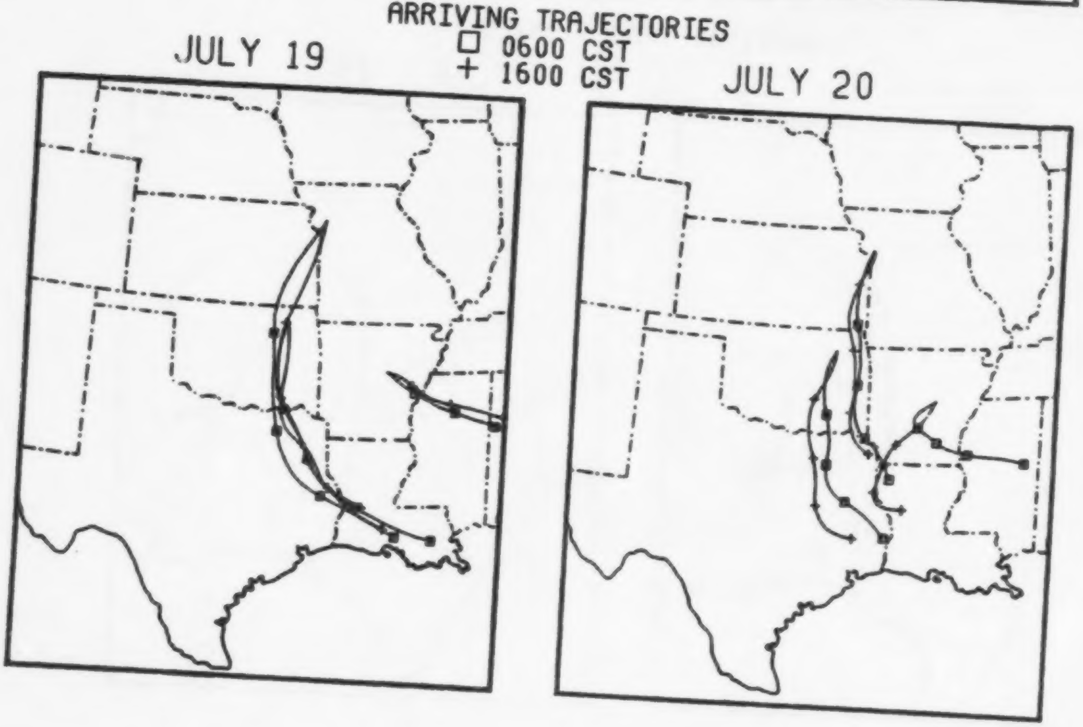

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
JULY 9
JULY 10


ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
JULY 11
JULY 12


ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
JULY 13
JULY 14


ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
JULY 15
JULY 16


ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
JULY 17
JULY 18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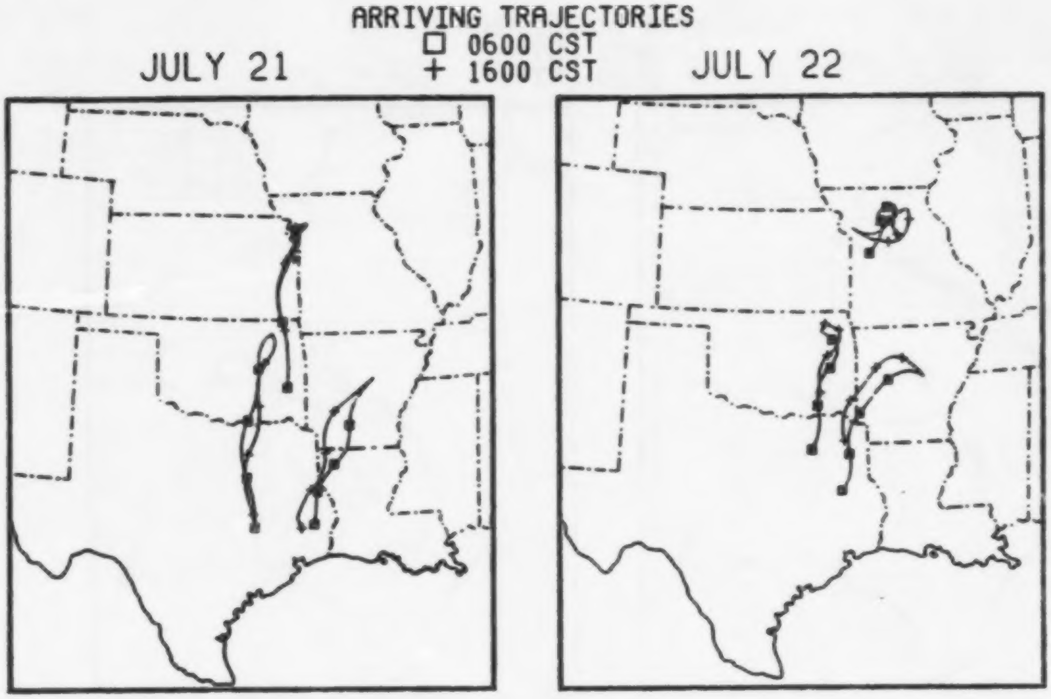
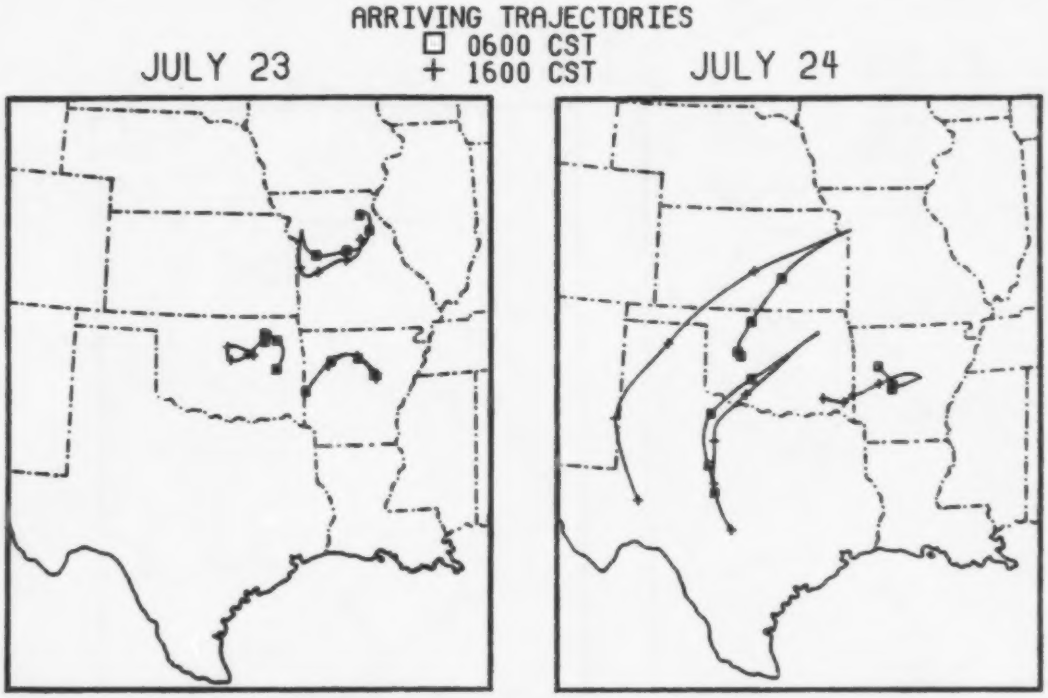
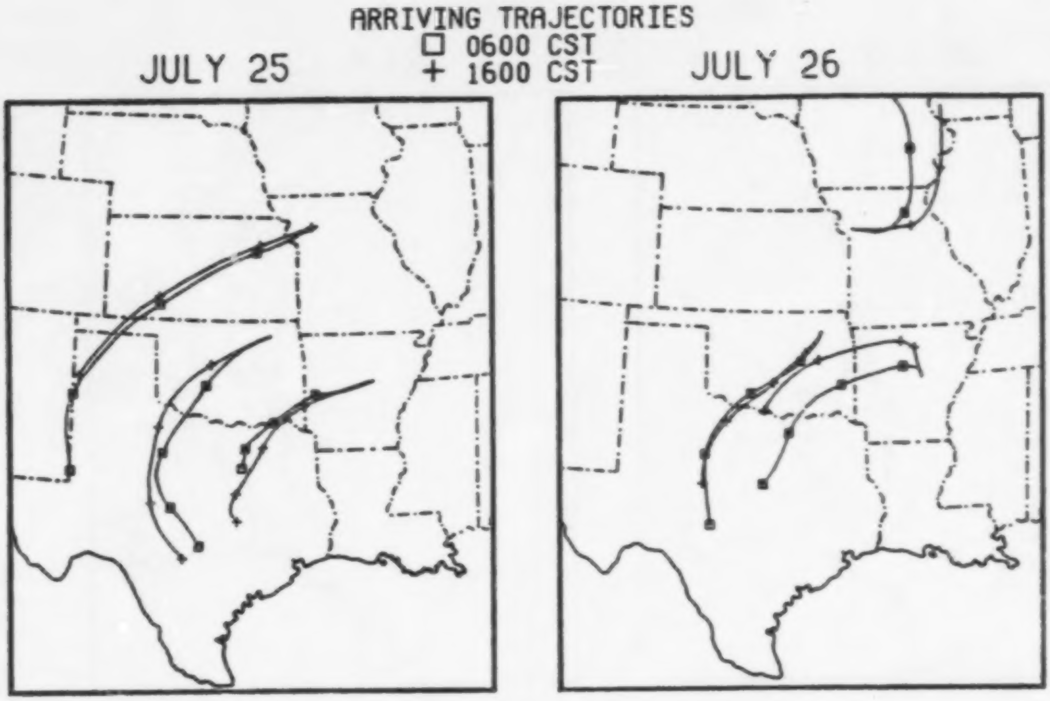
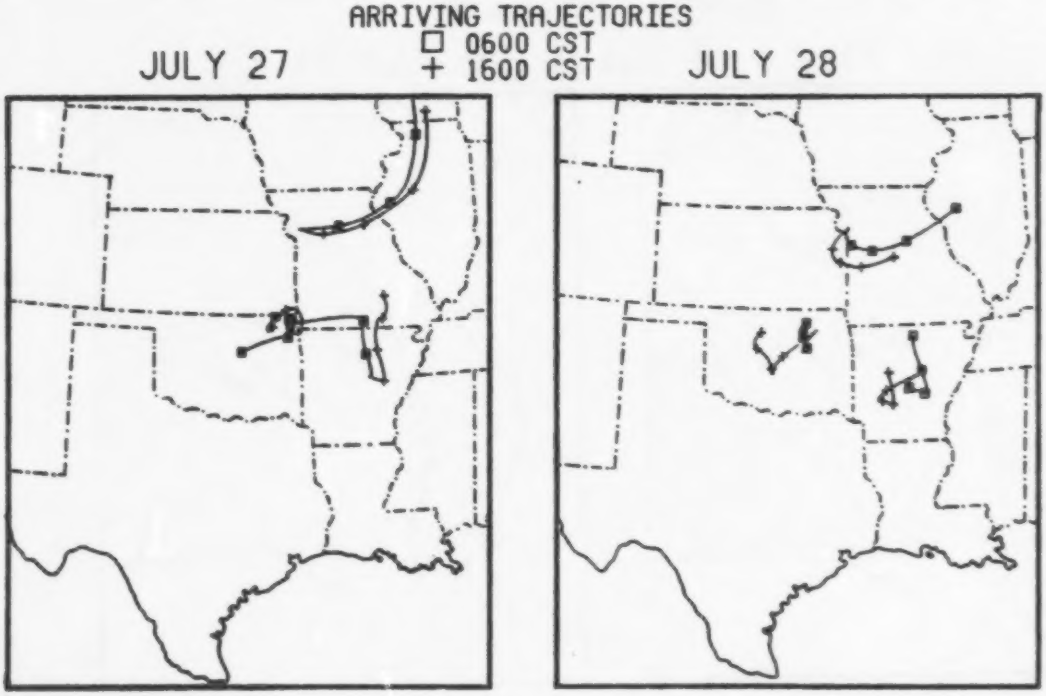
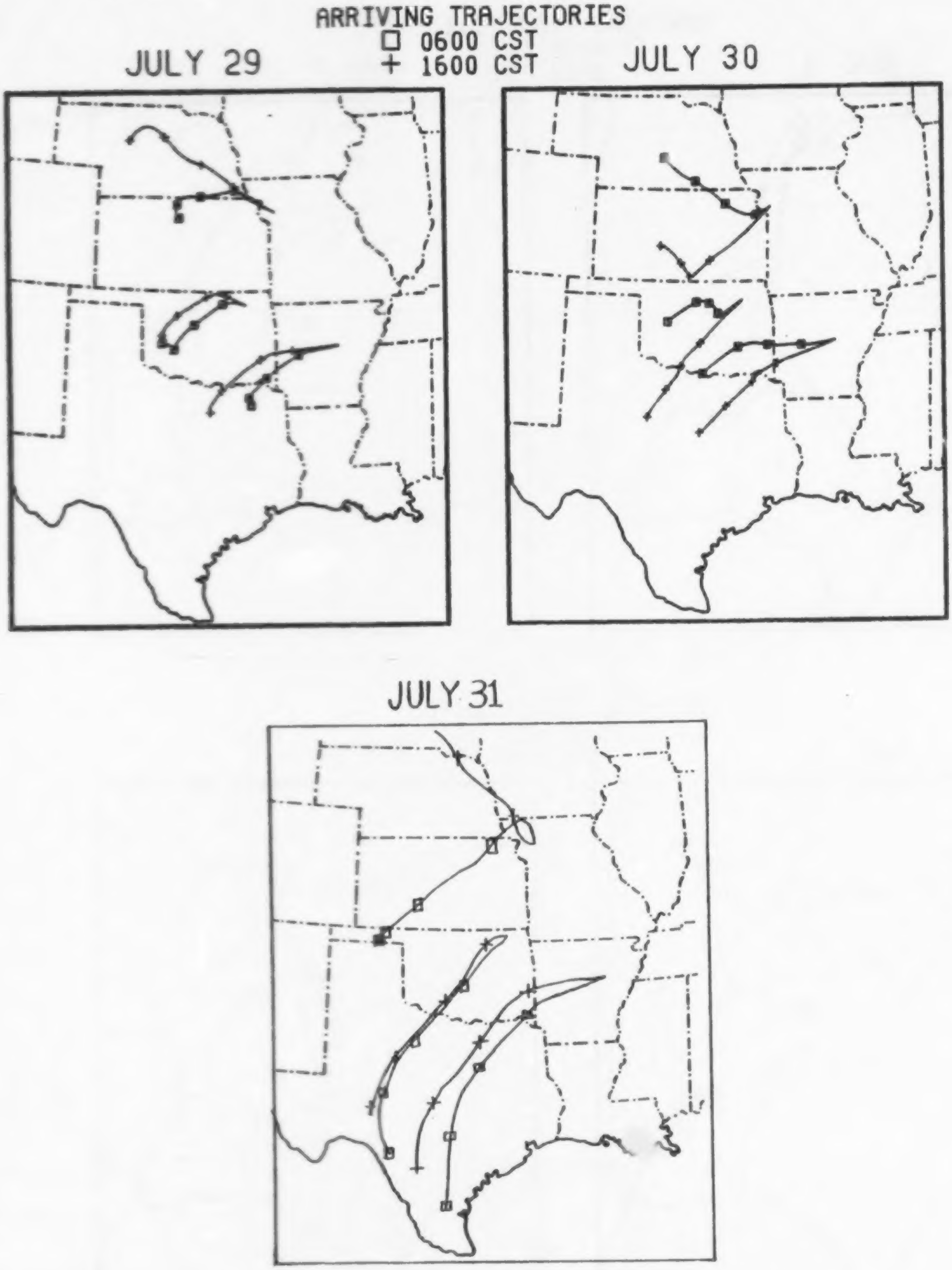
□ 0600 CST
+ 1600 CST
JULY 19
JULY 20

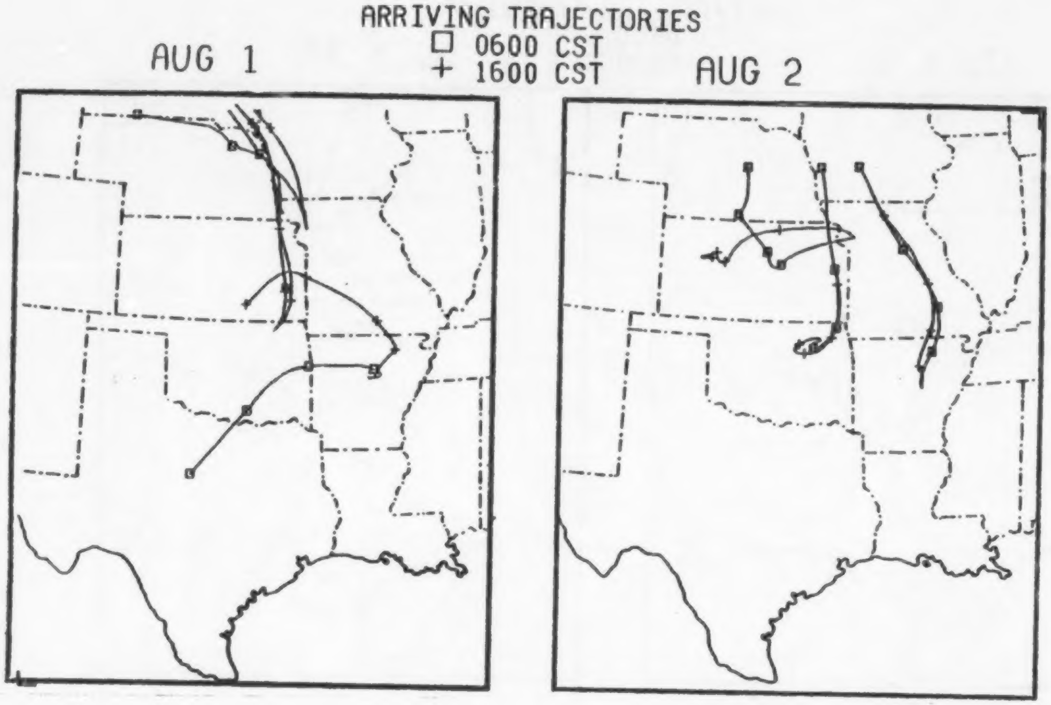

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
JULY 21
JULY 22

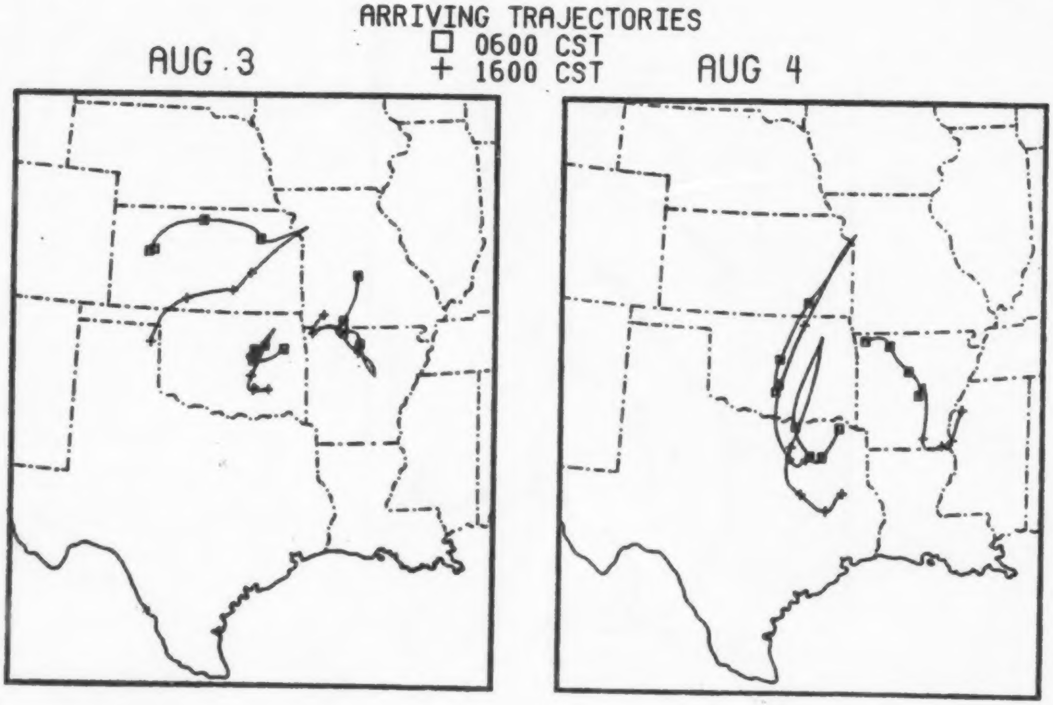

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
JULY 23
JULY 24

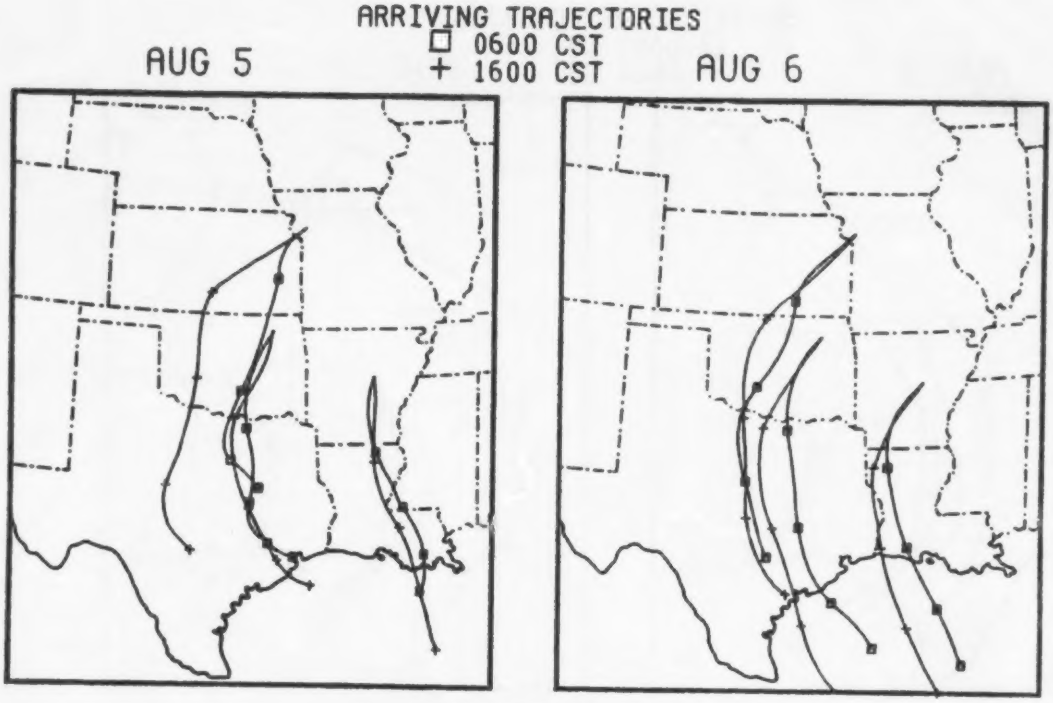

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
JULY 25
JULY 26

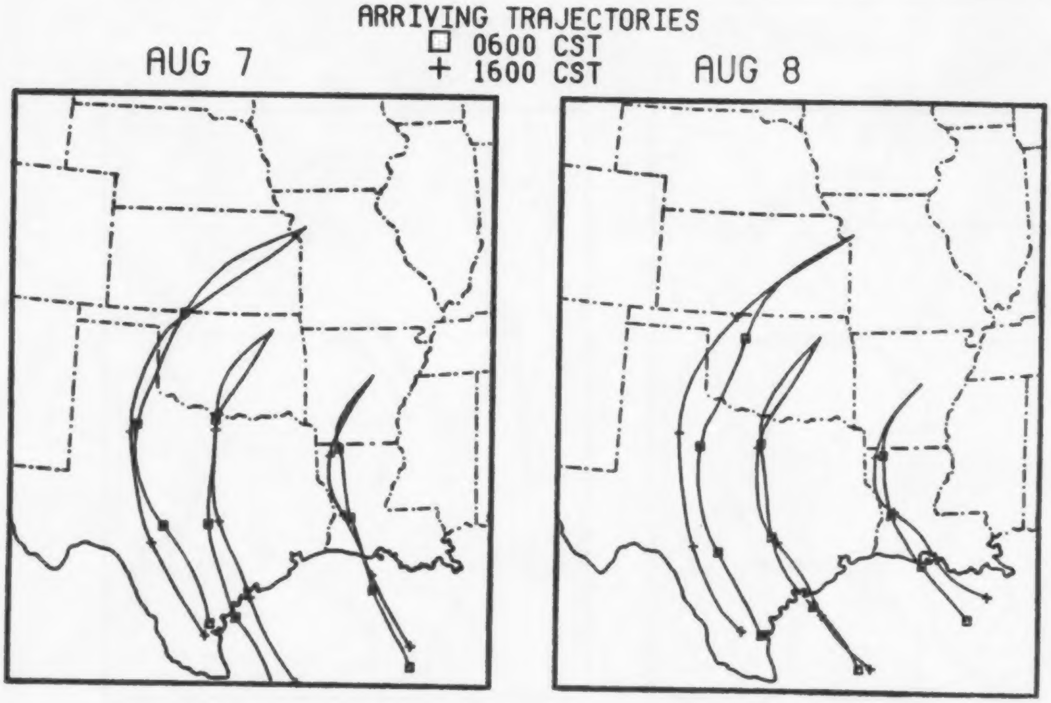

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
JULY 27
JULY 28


ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
JULY 29
JULY 30
JULY 31


ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
AUG 1
AUG 2


ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
AUG 3
AUG 4


ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
AUG 5
AUG 6


ARRIVING TRAJECTORIES
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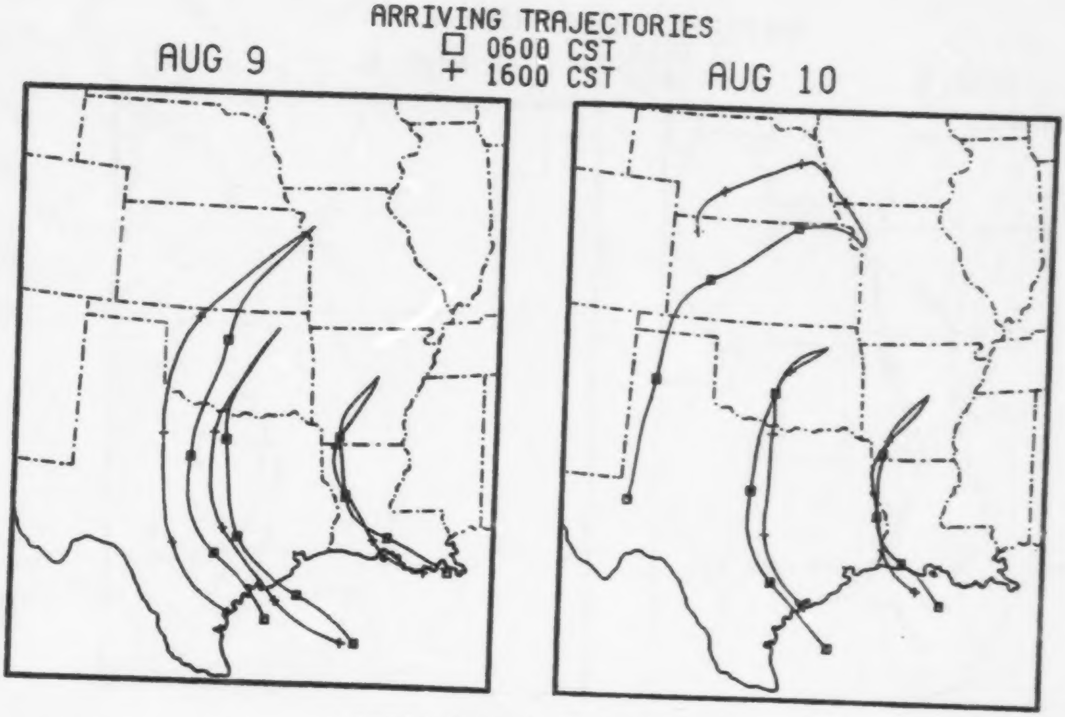
+ 1600 CST
AUG 7
AUG 8


ARRIVING TRAJECTORIES
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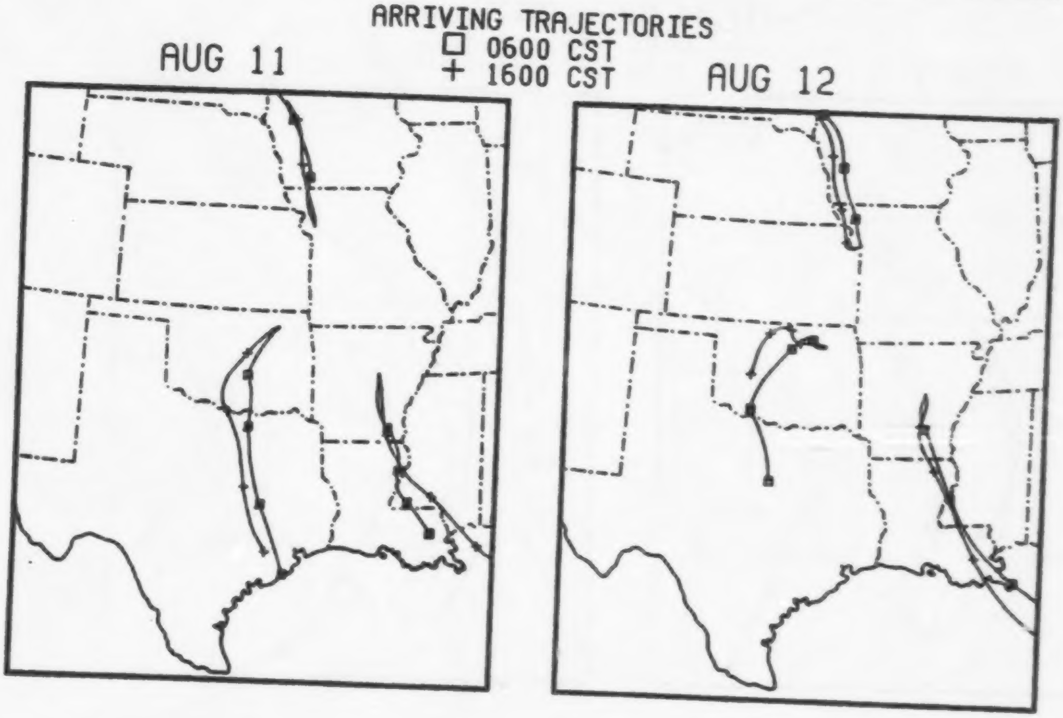
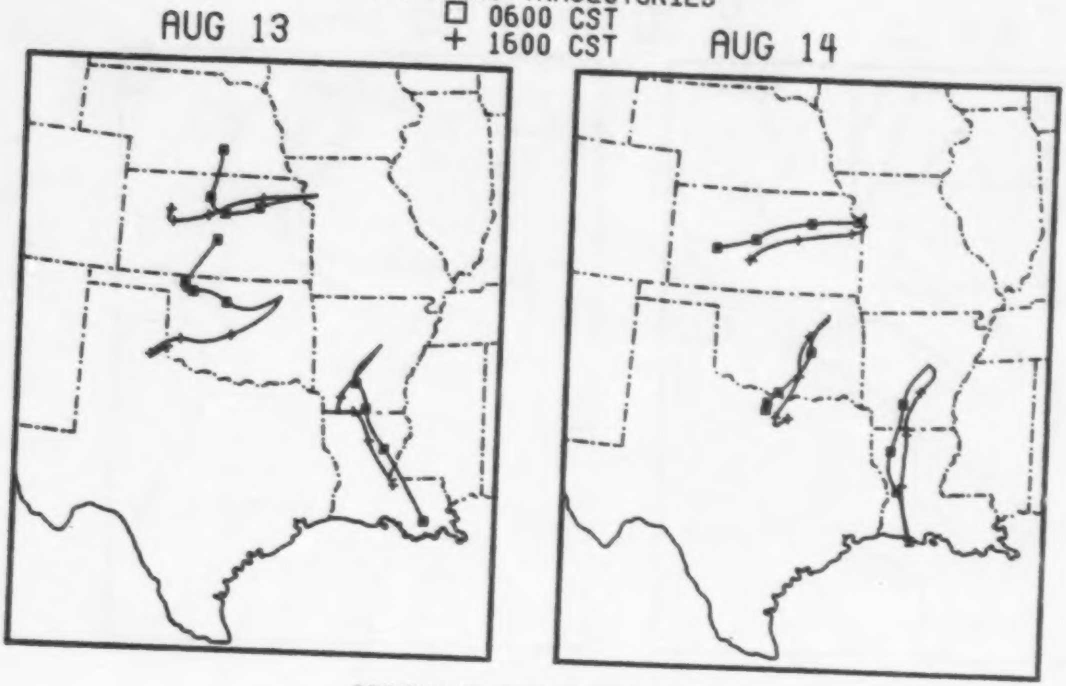
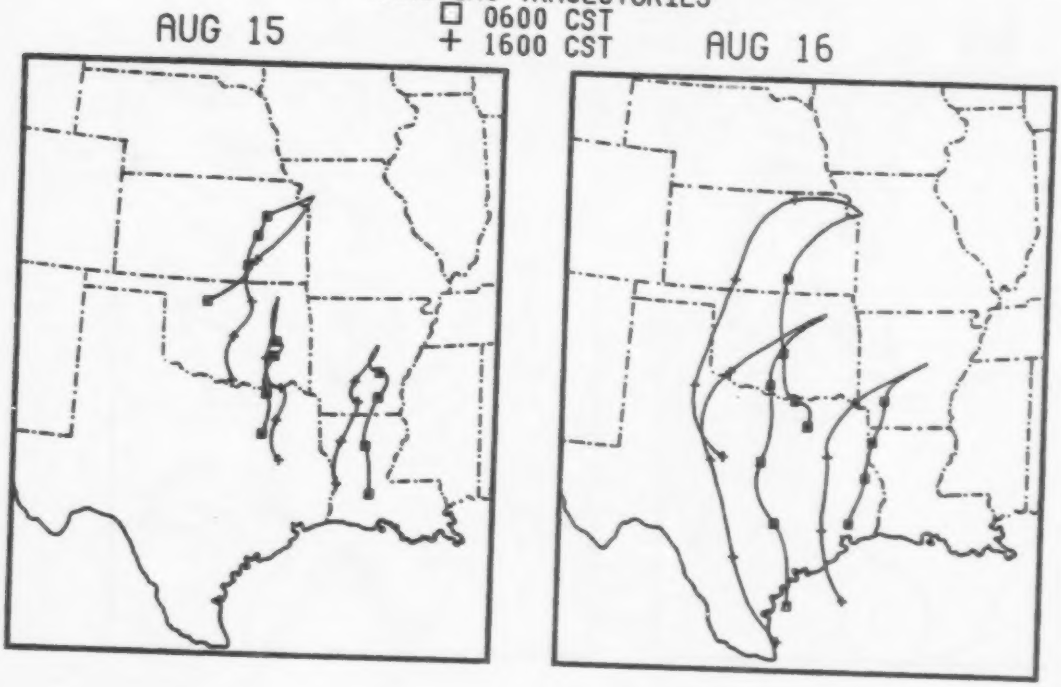
+ 1600 CST
AUG 9
AUG 10


ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
AUG 11
AUG 12

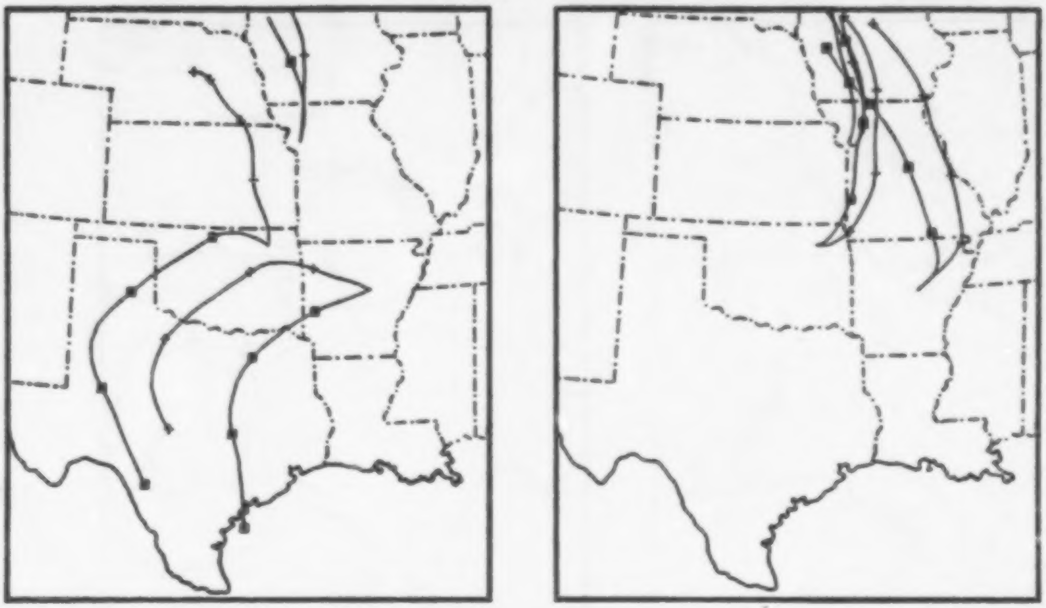
ARRIVING TRAJECTORIES


□ 0600 CST
+ 1600 CST
AUG 13
AUG 14

ARRIVING TRAJECTORIES


□ 0600 CST
+ 1600 CST
AUG 15
AUG 16

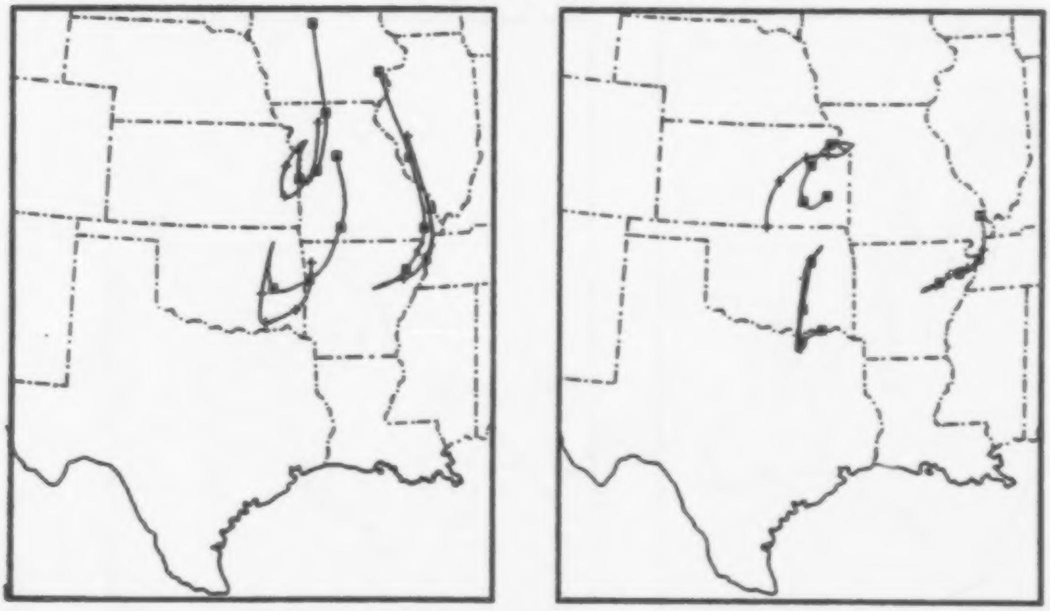
ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST



AUG 17

AUG 18

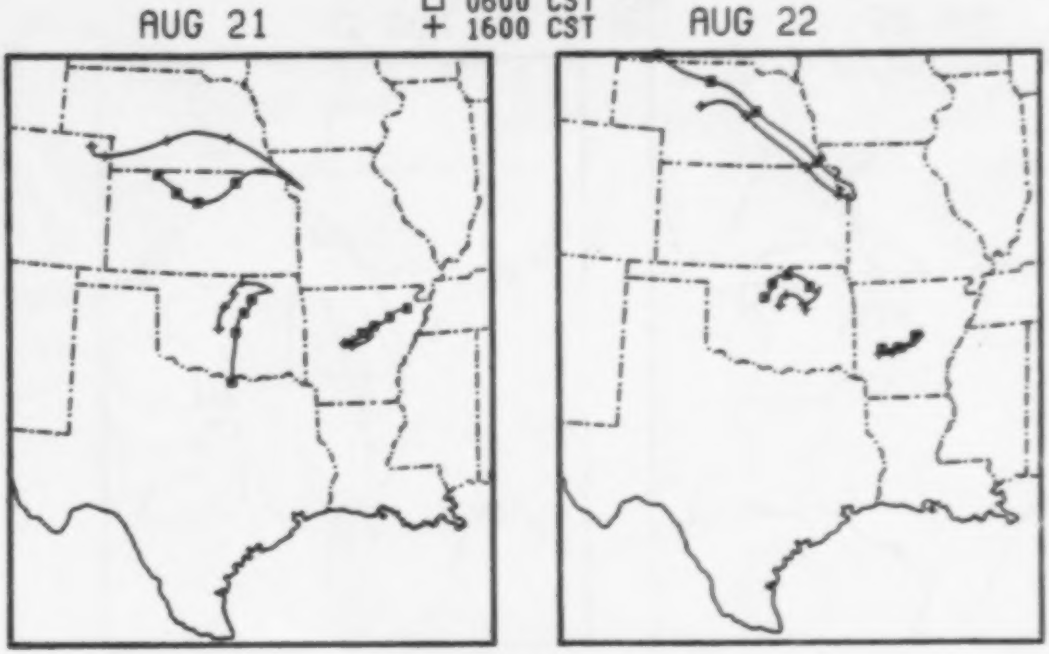
ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST



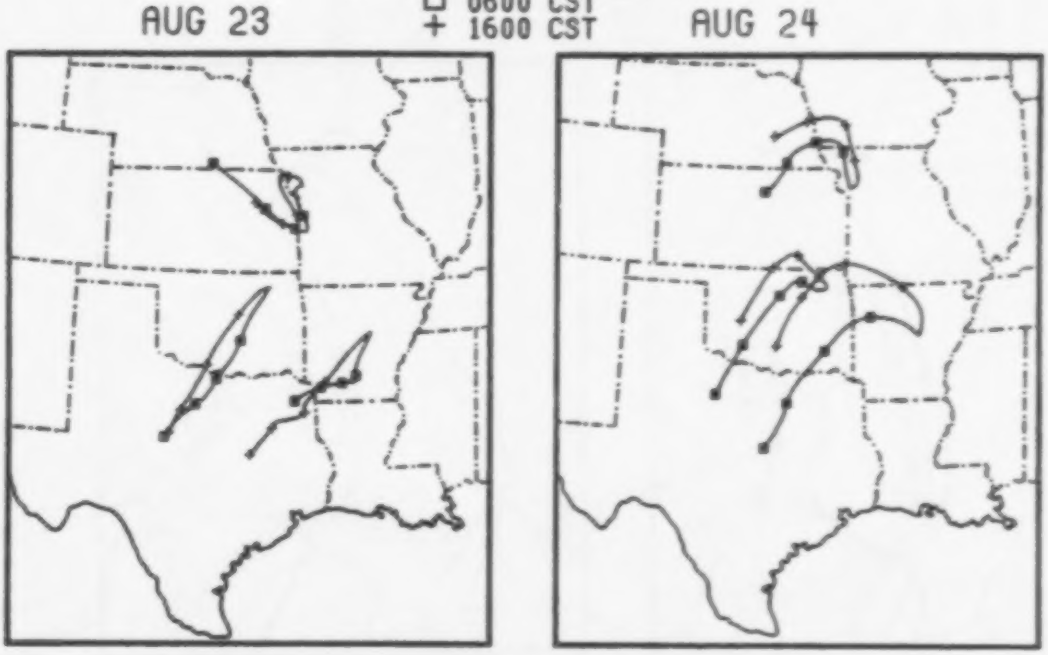
AUG 19

AUG 20

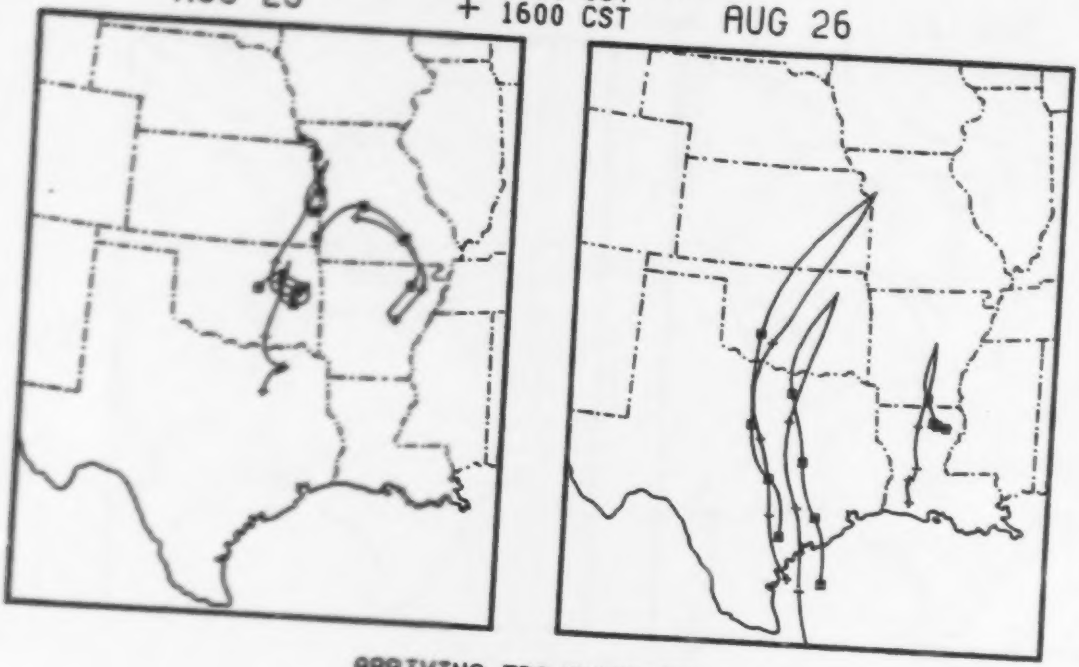
ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST


AUG 21
AUG 22

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST

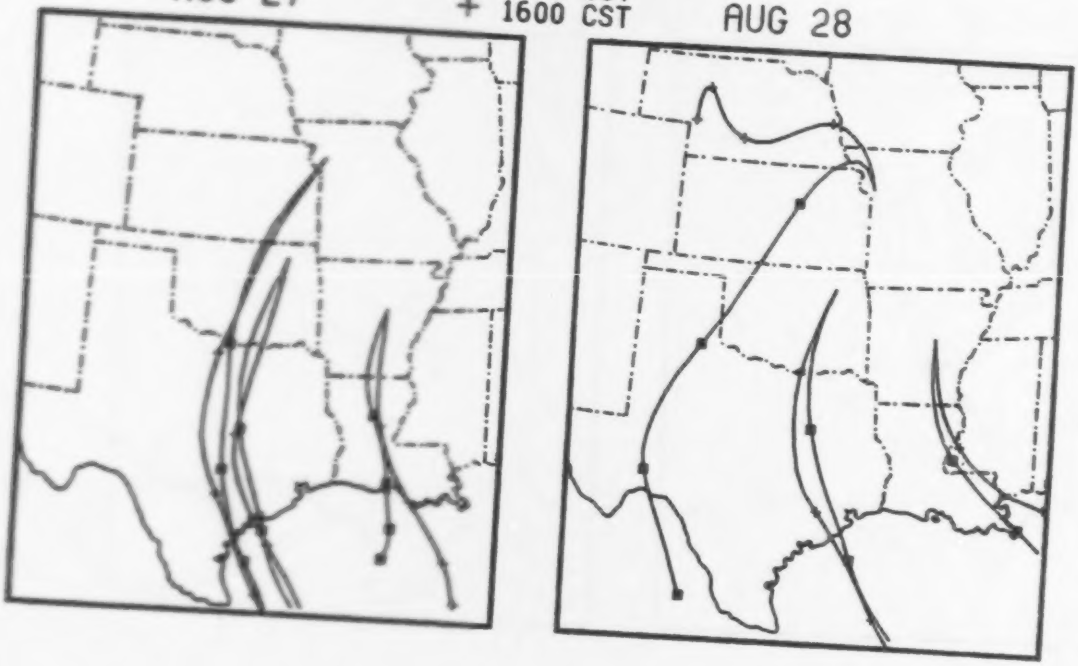

AUG 23
AUG 24

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST


AUG 25

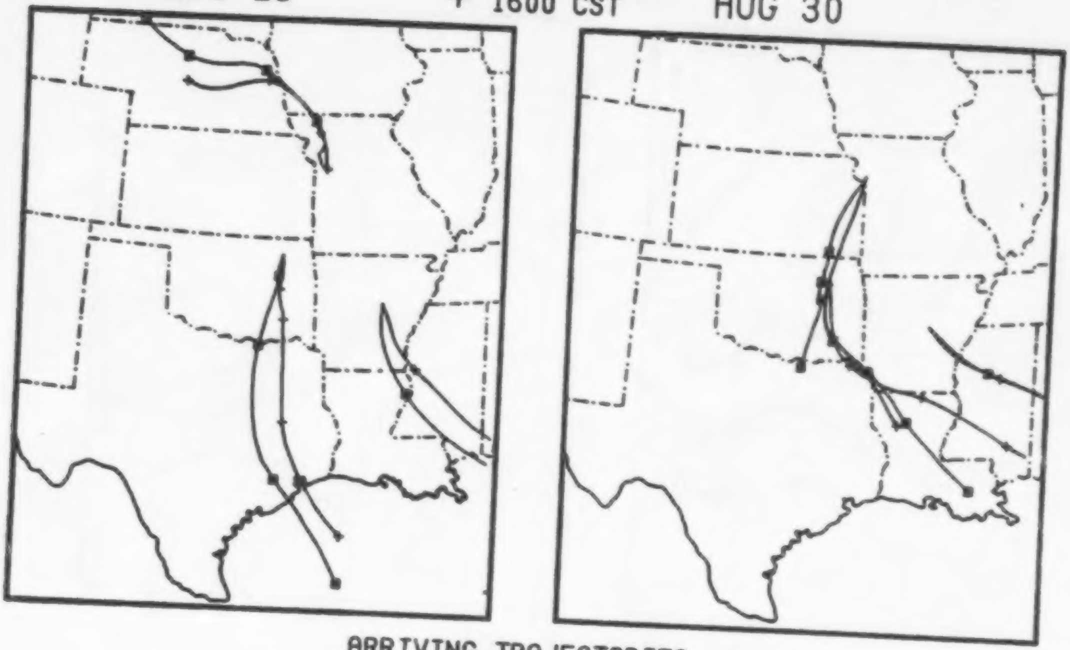
AUG 26

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST


AUG 27

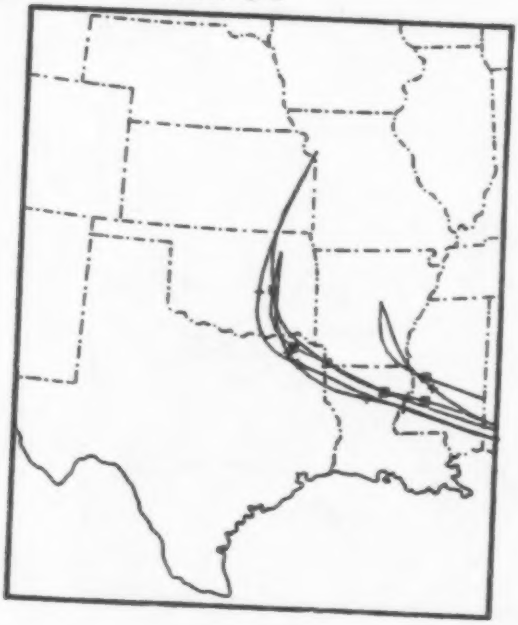
AUG 28

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST


AUG 29

AUG 30

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST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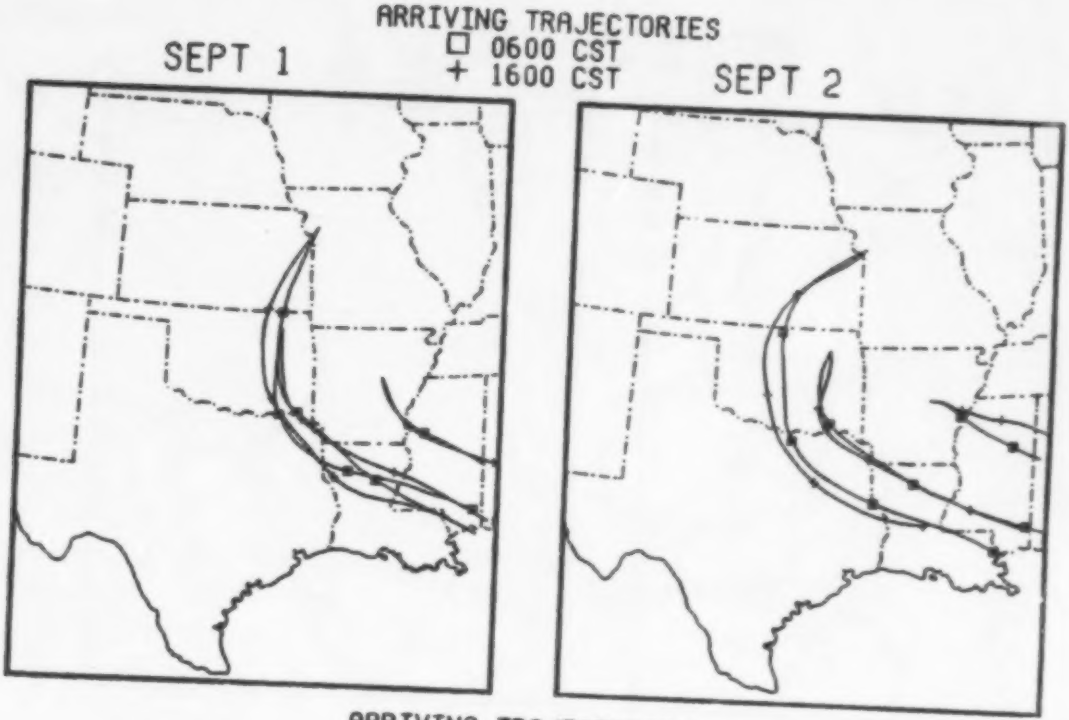
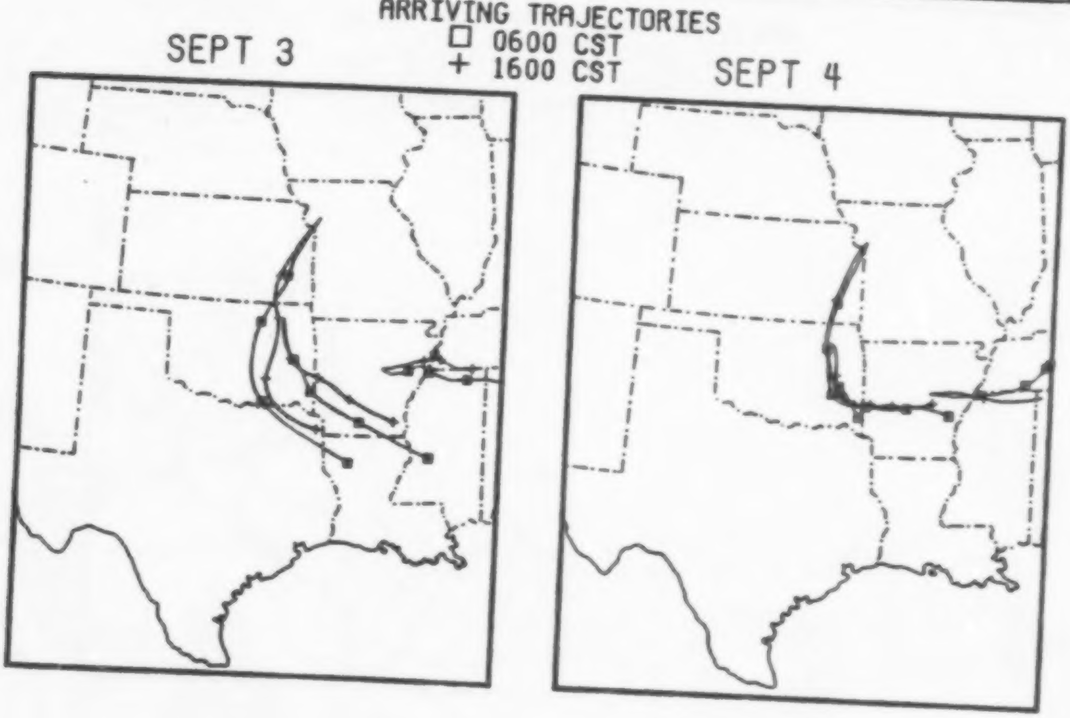
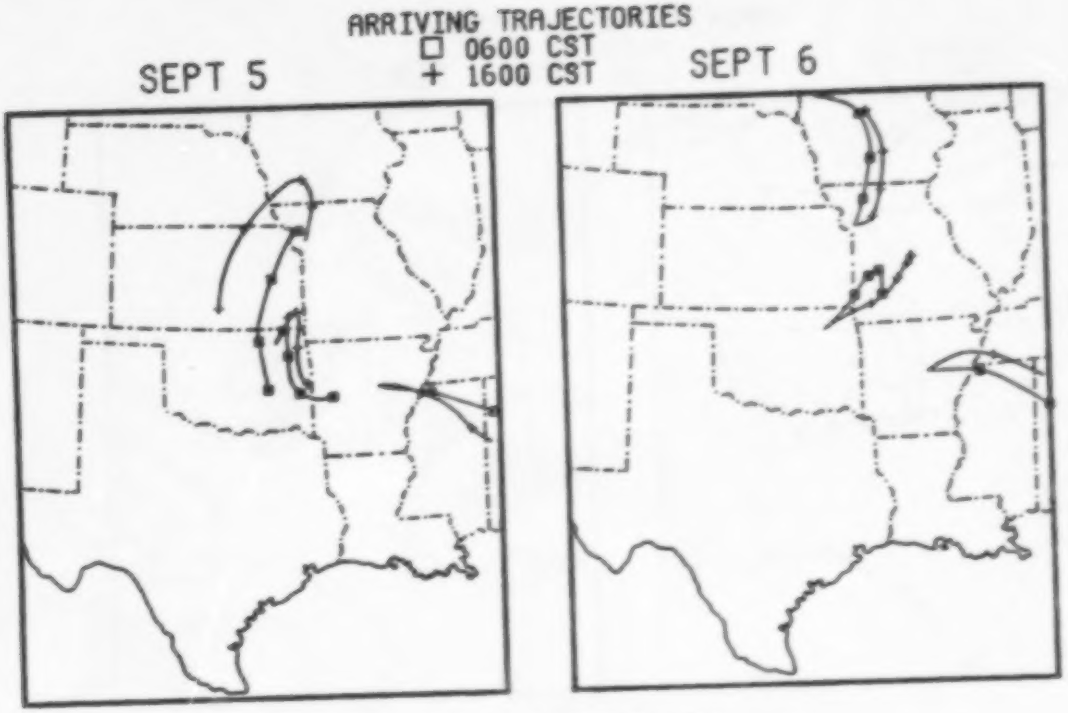
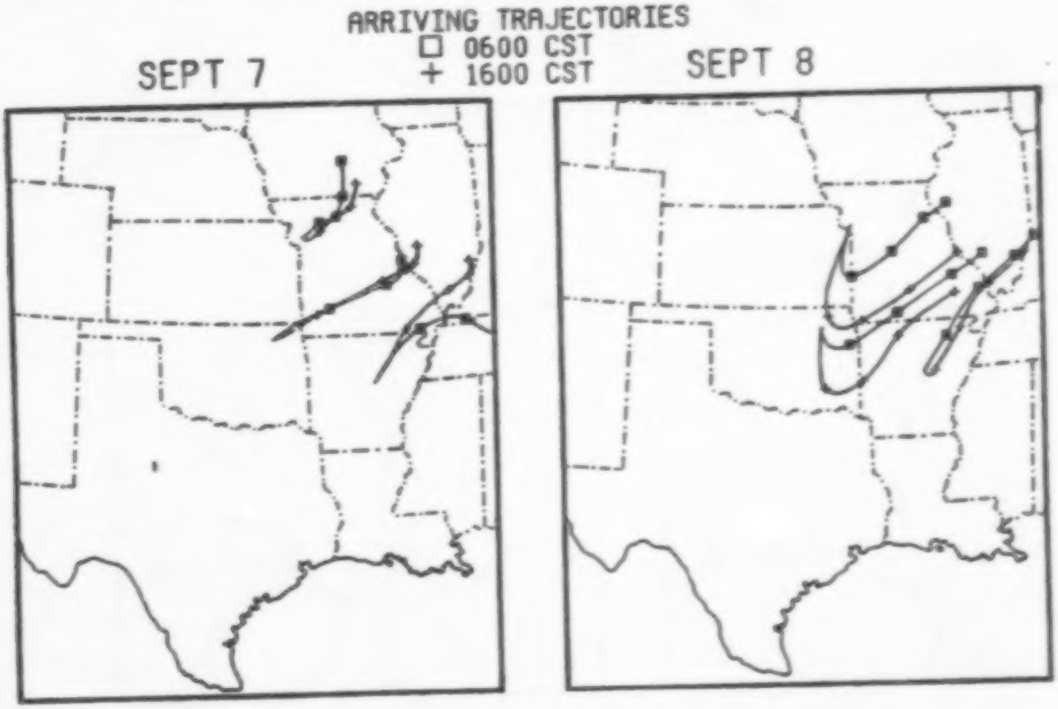
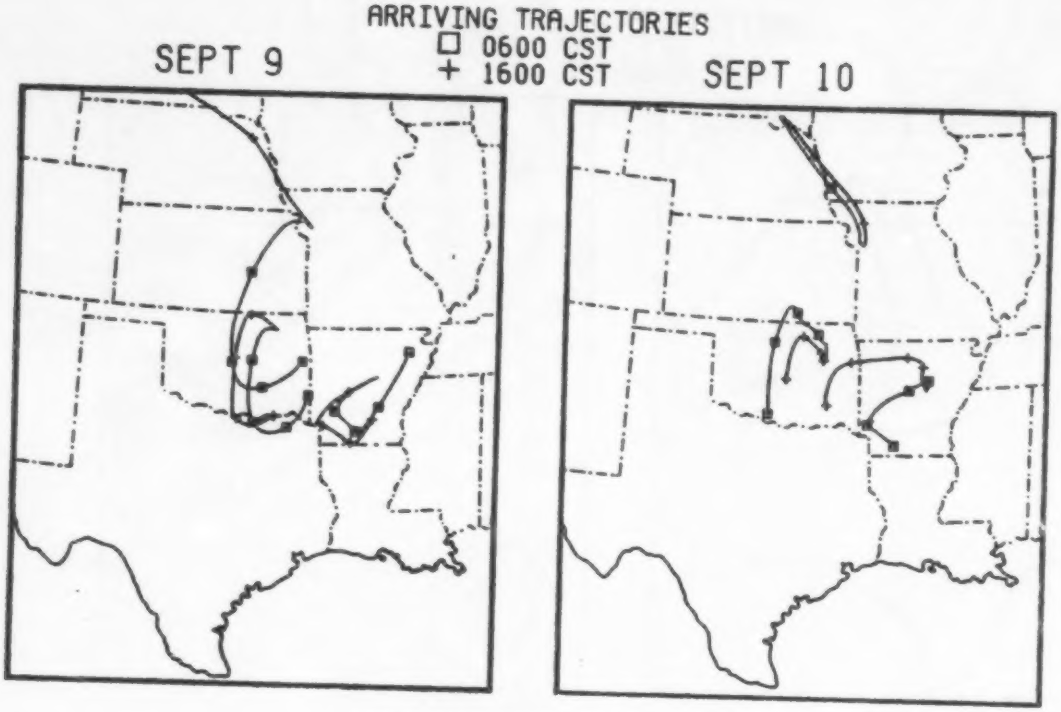
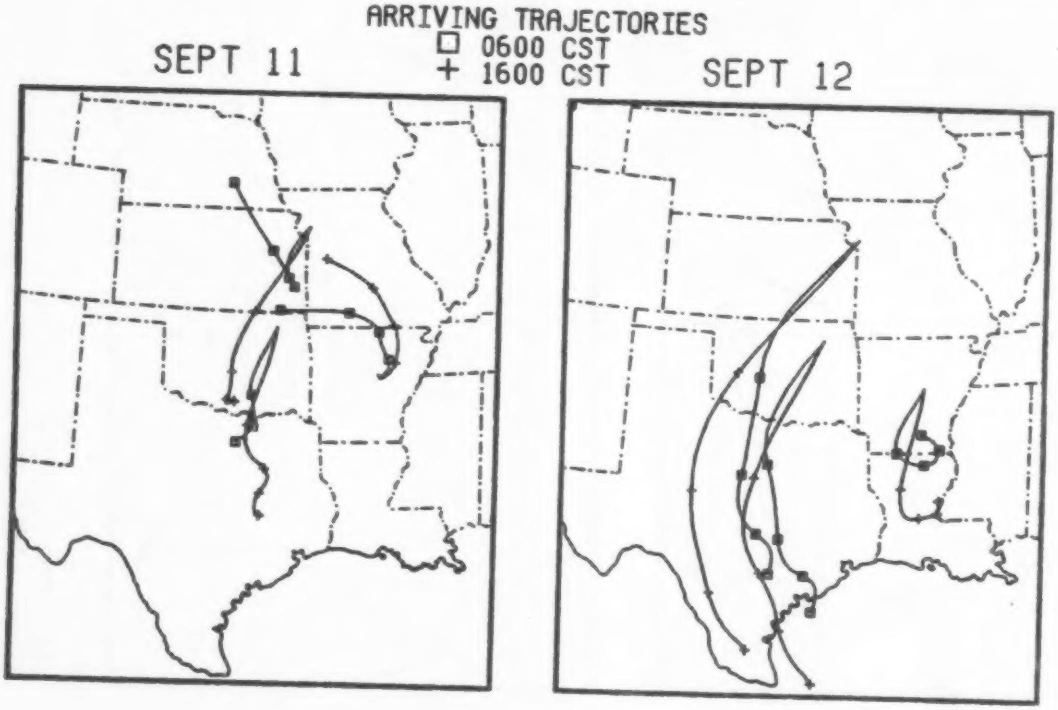

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
SEPT 1
SEPT 2

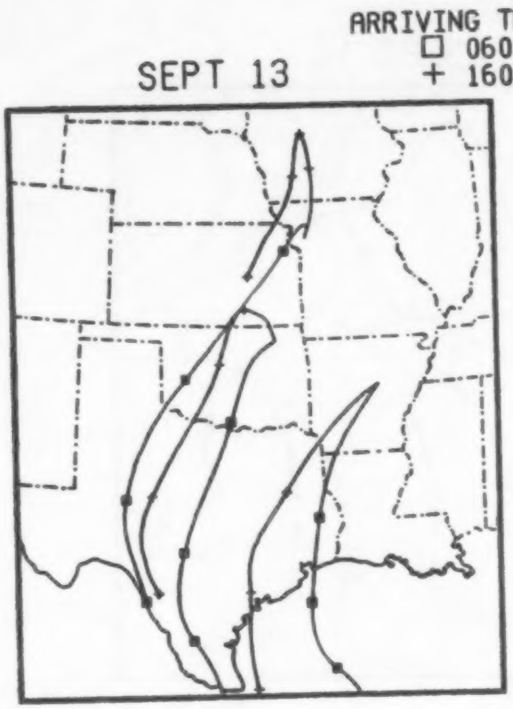

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
SEPT 3
SEPT 4

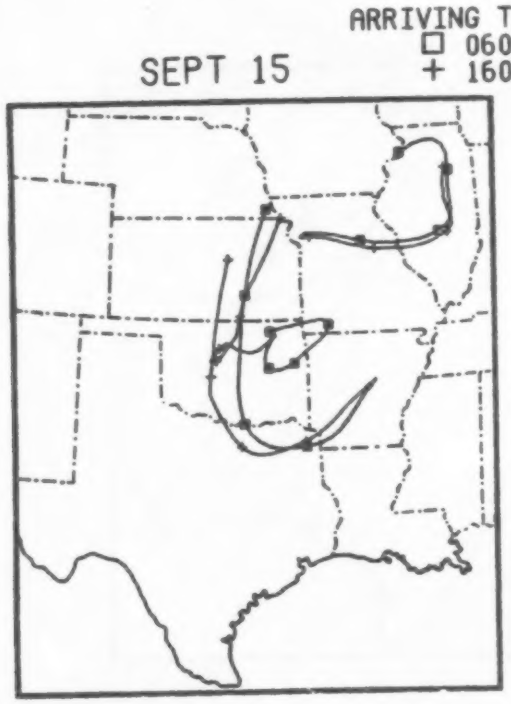

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
SEPT 5
SEPT 6

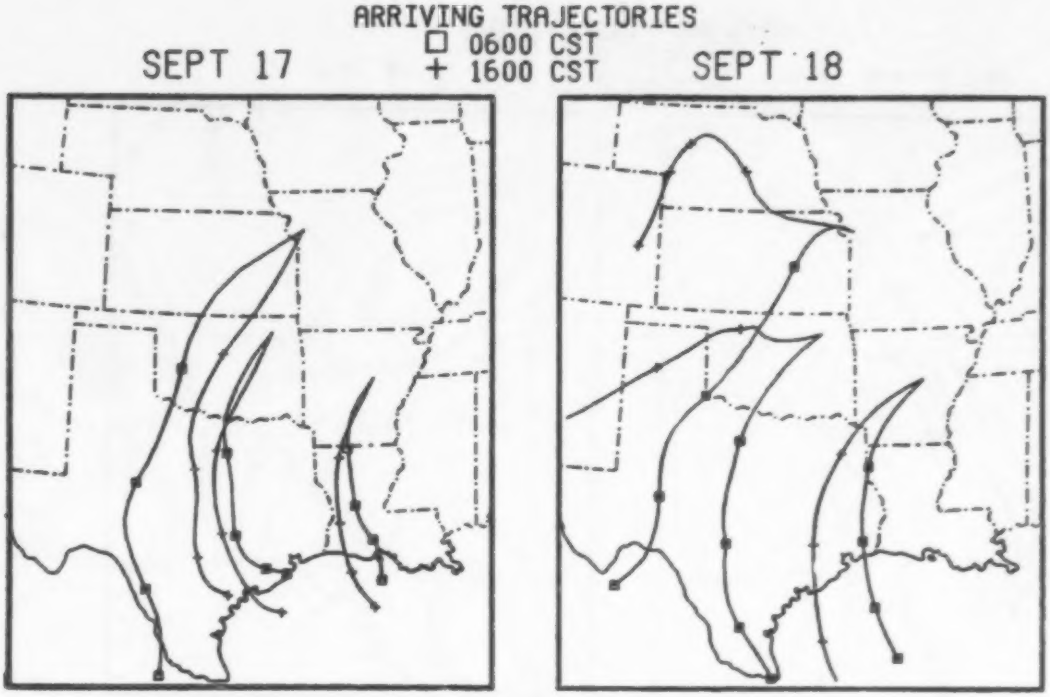

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
SEPT 7
SEPT 8

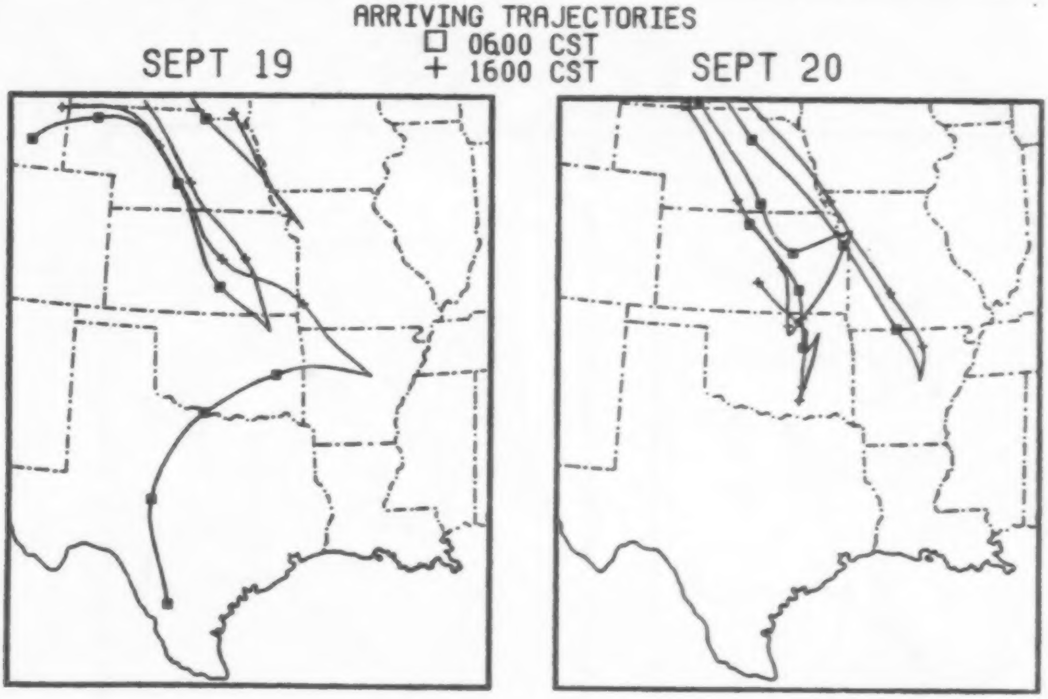

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
SEPT 9
SEPT 10

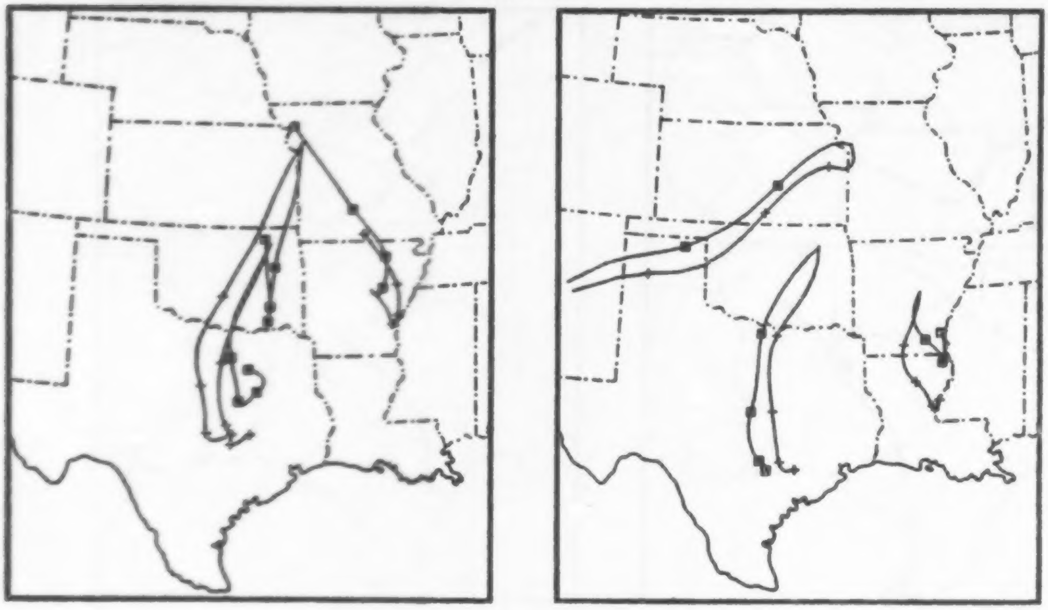

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
SEPT 11
SEPT 12


ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
SEPT 13
SEPT 14


ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
SEPT 15
SEPT 16


ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
SEPT 17
SEPT 18


ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
SEPT 19
SEPT 20

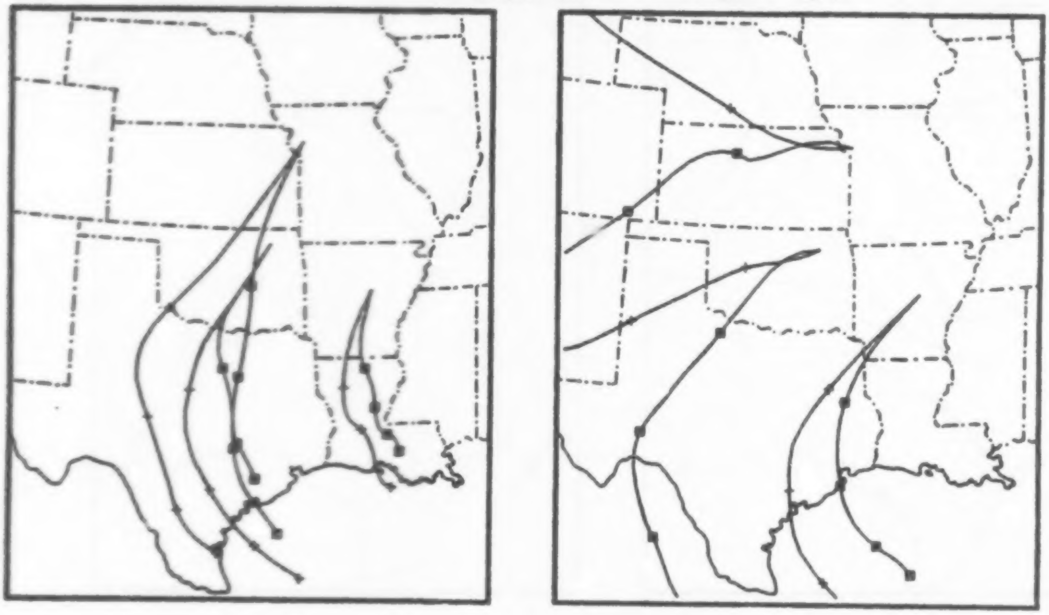


ARRIVING TRAJECTORIES

□ 0600 CST
+ 1600 CST

SEPT 21

SEPT 22



ARRIVING TRAJECTORIES

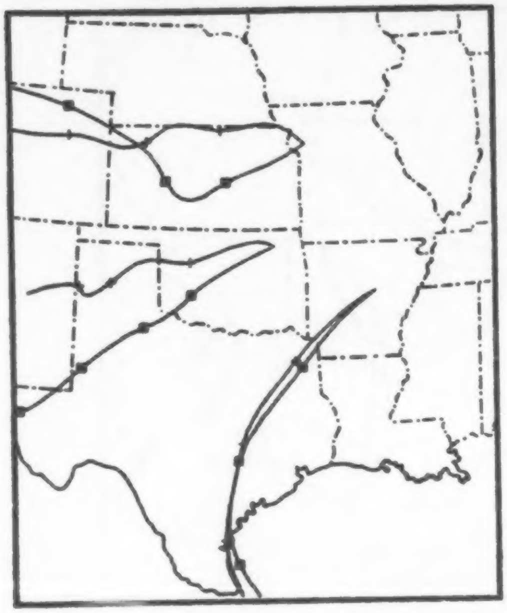
□ 0600 CST
+ 1600 CST

SEPT 23

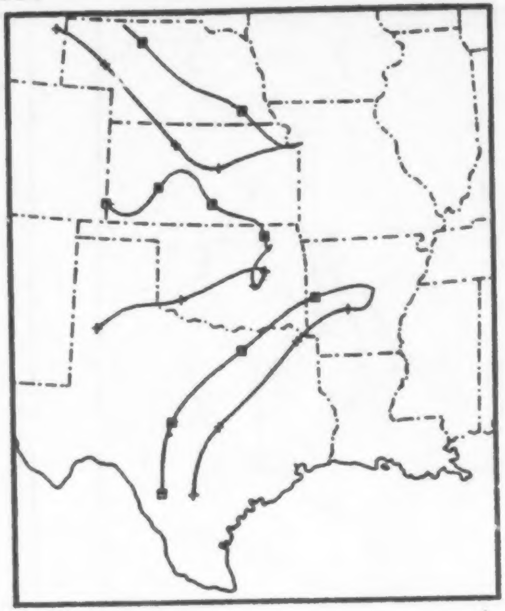
SEPT 24

ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST

SEPT 25

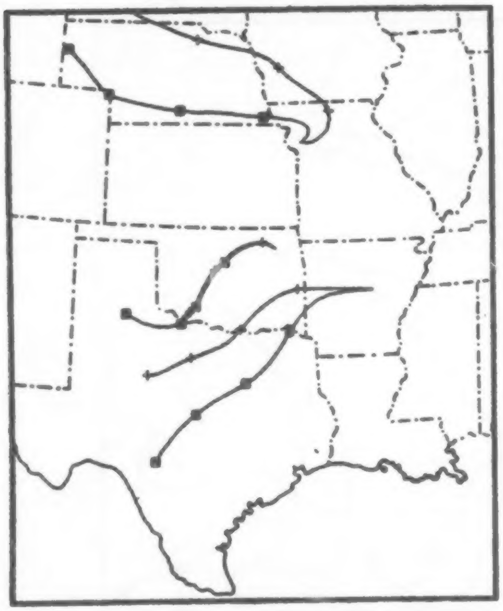


SEPT 26

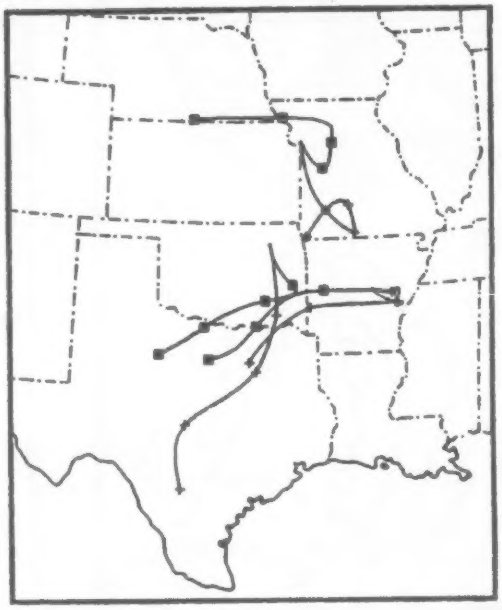


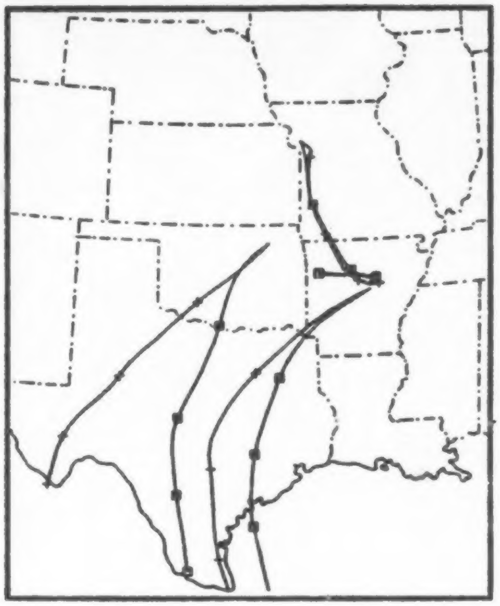
ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST

SEPT 27



SEPT 28





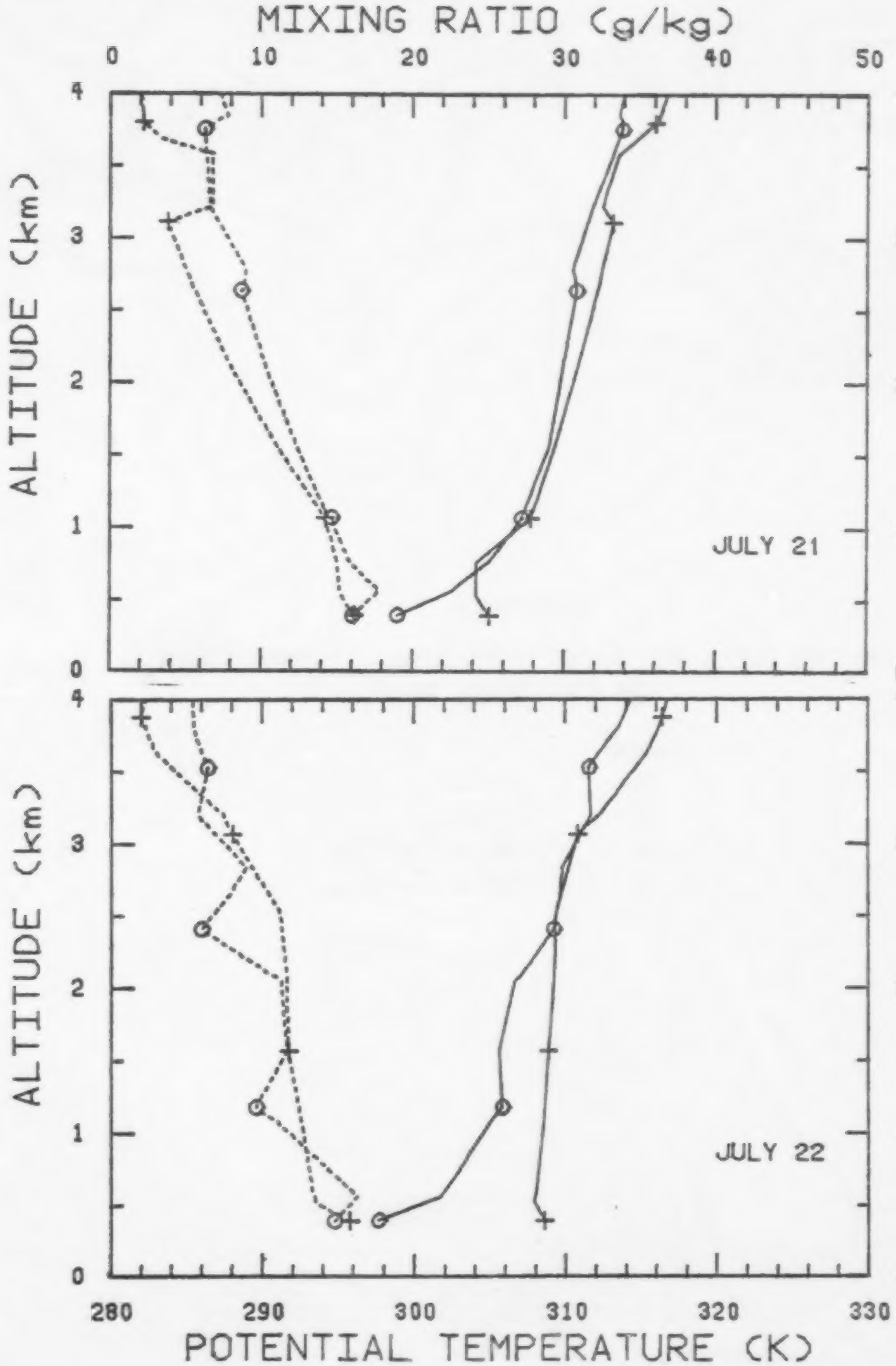
ARRIVING TRAJECTORIES
□ 0600 CST
+ 1600 CST
SEPT 29

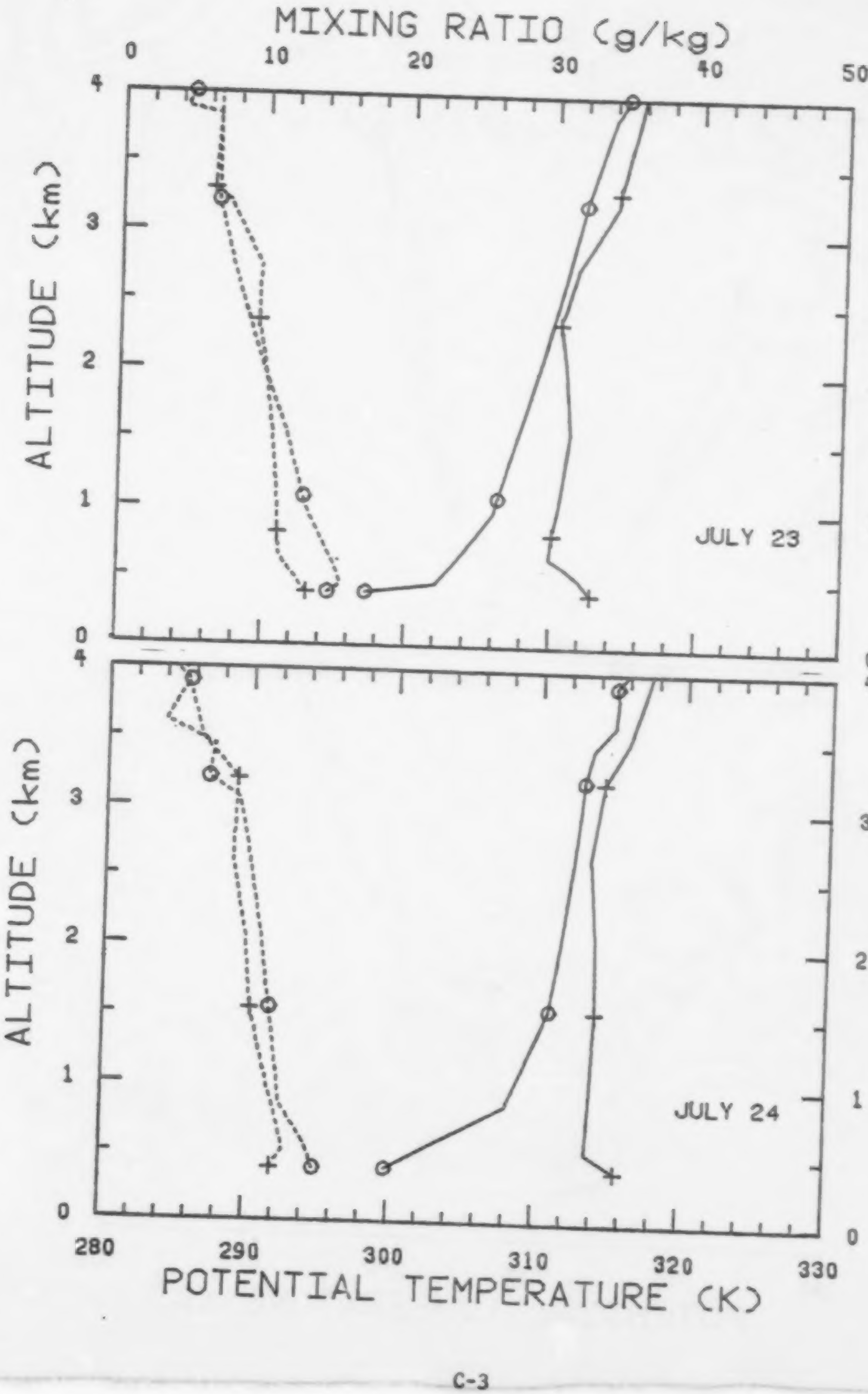
## APPENDIX C

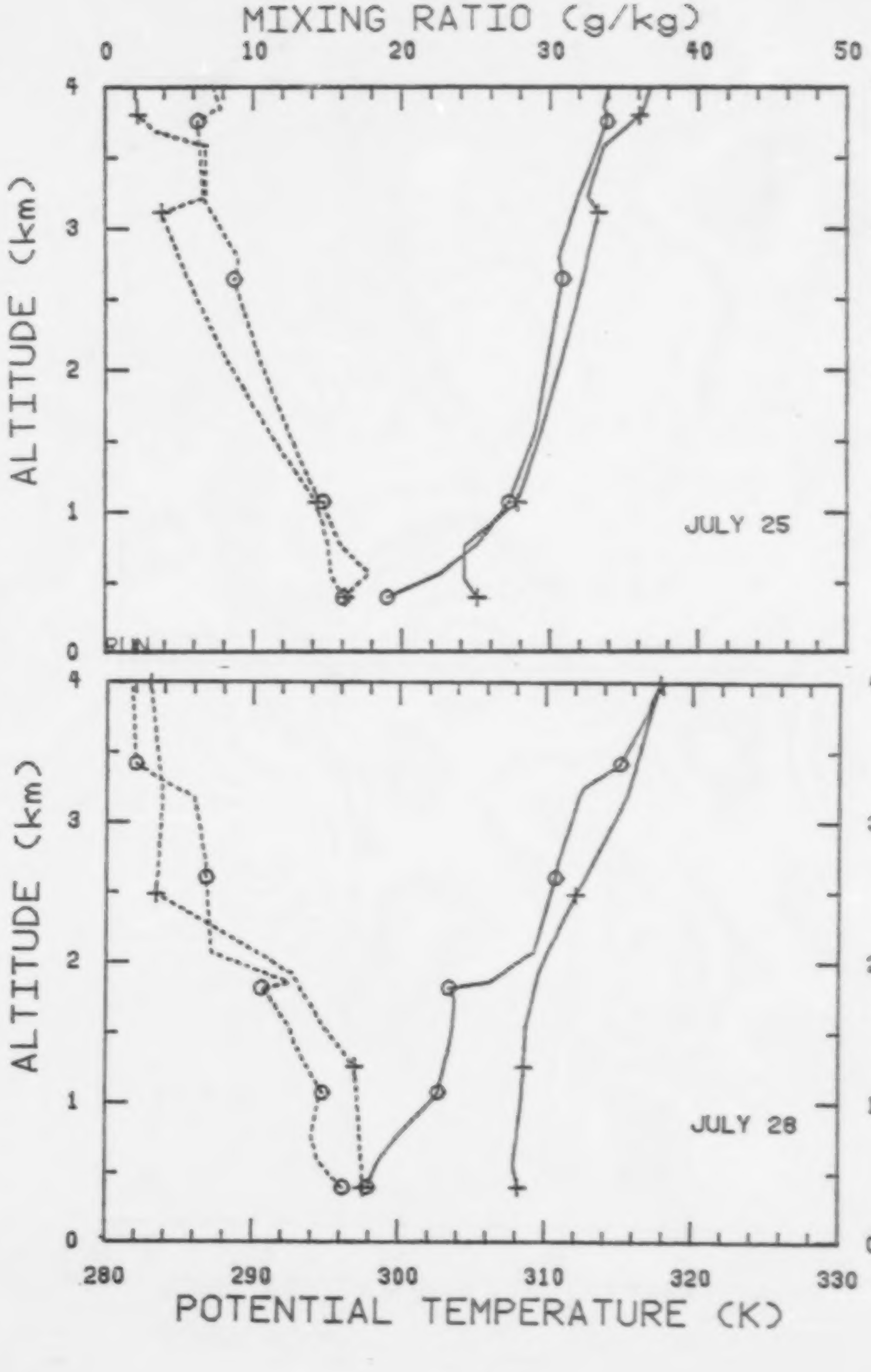
## MIXING DEPTH AND ATMOSPHERIC STABILITY PARAMETERS FOR CASE STUDY DAYS

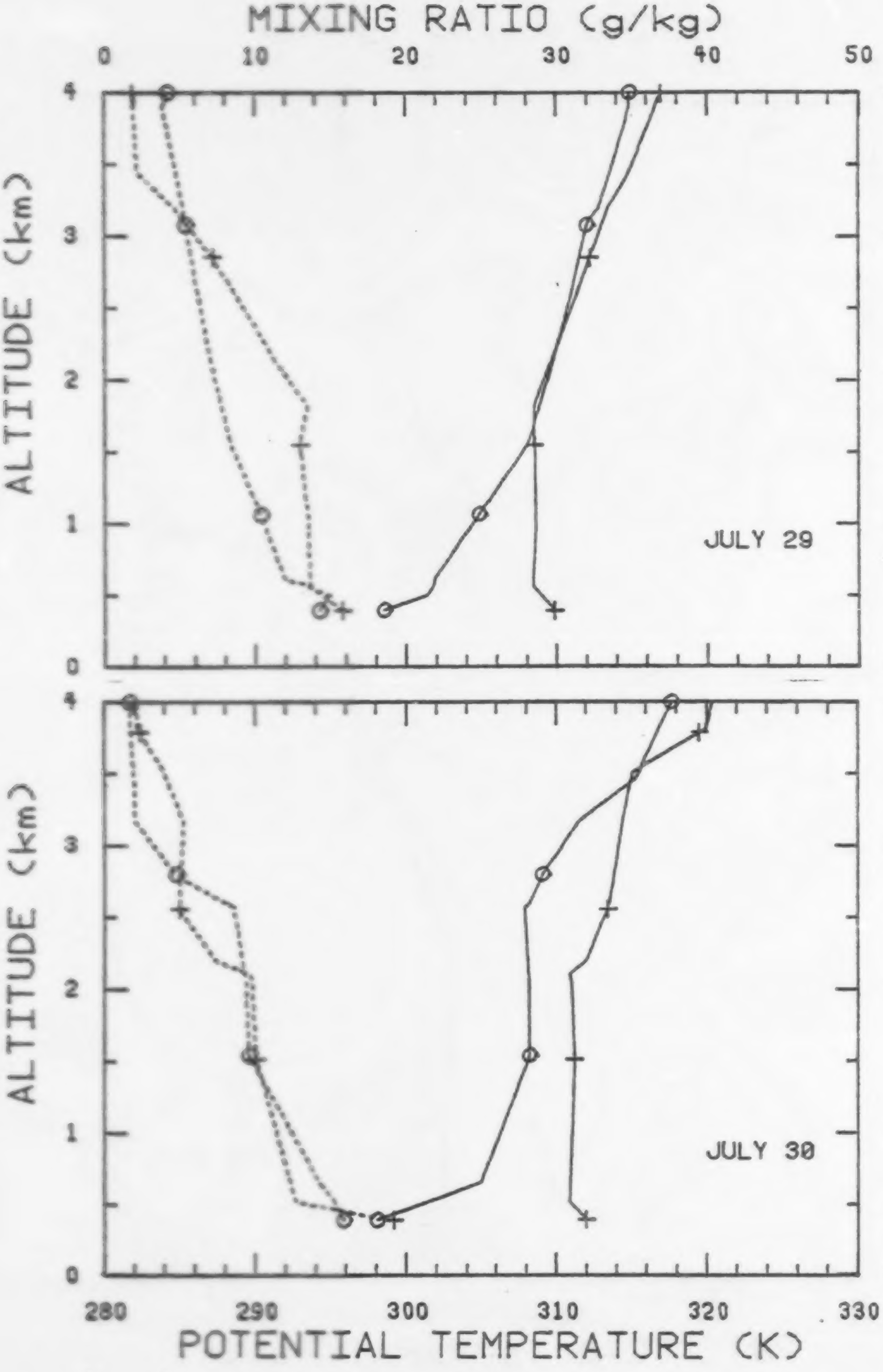
**Legend**

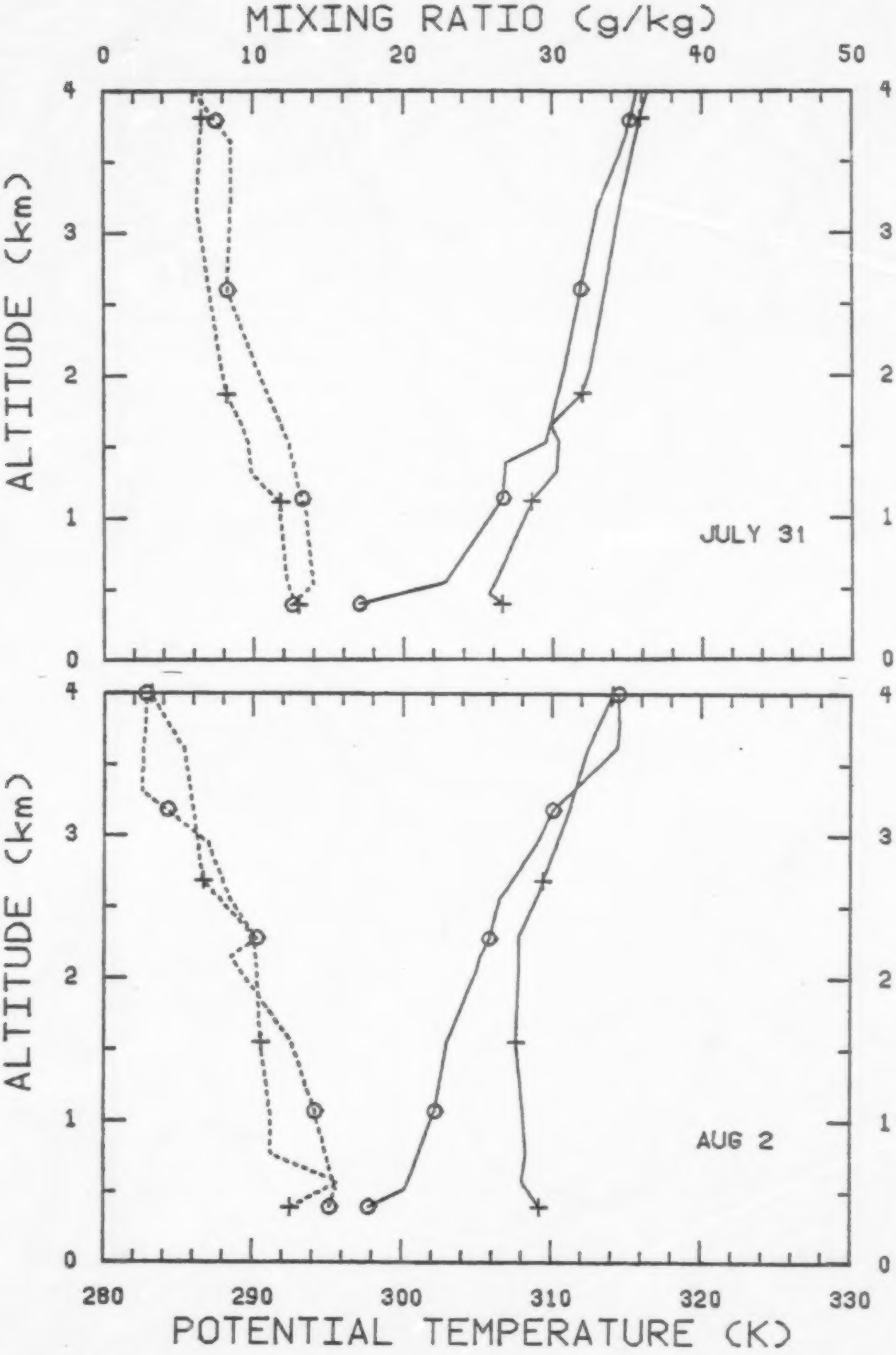
| | |
|---|---|
| $\theta$ | solid line |
| R | dashed line |
| + | 1800 CST sounding |
| O | 0600 CST sounding |

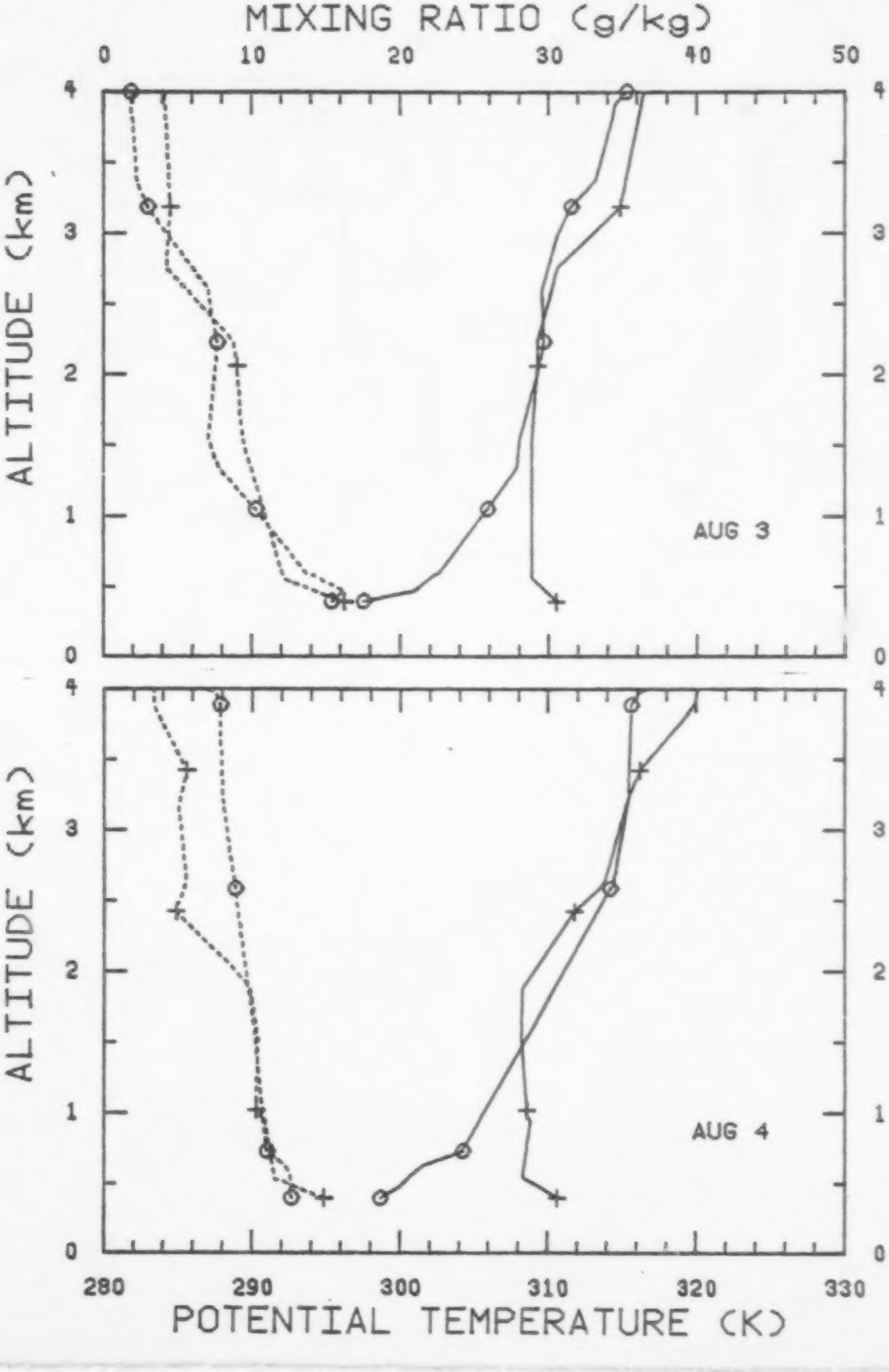

MIXING RATIO (g/kg)
0
10
20
30
40
50
ALTITUDE (km)
0
1
2
3
4
JULY 21
JULY 22
280
290
300
310
320
330
POTENTIAL TEMPERATURE (K)

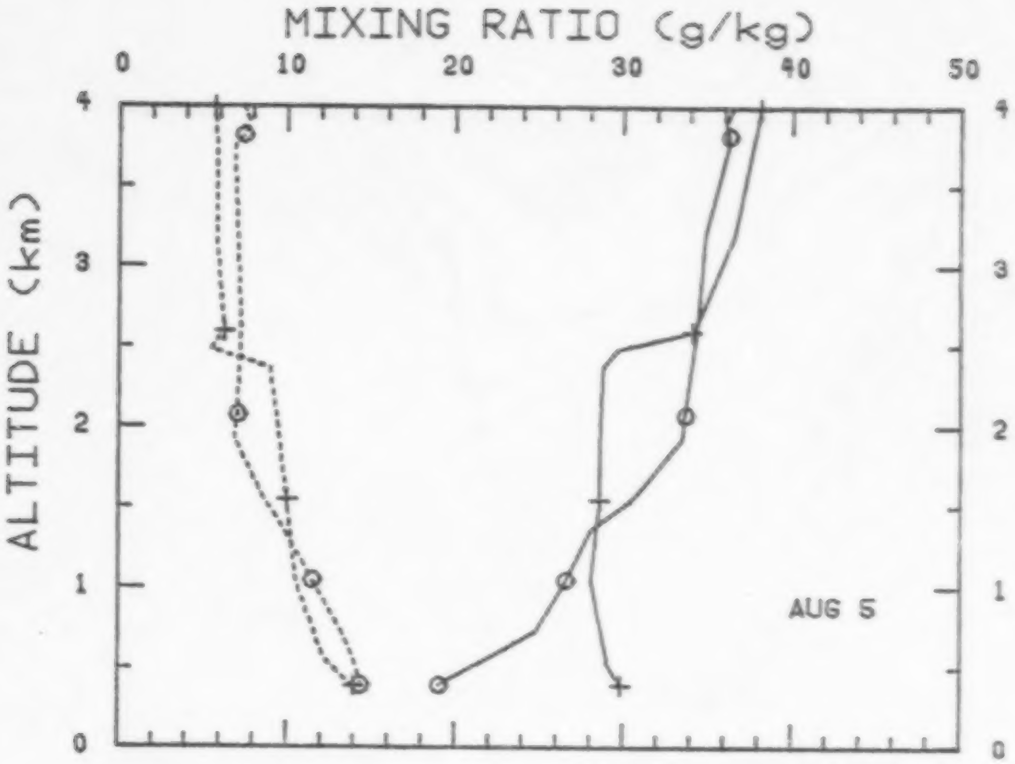

MIXING RATIO (g/kg)
0
10
20
30
40
50
ALTITUDE (km)
0
1
2
3
4
JULY 23
ALTITUDE (km)
JULY 24
280
290
300
310
320
330
POTENTIAL TEMPERATURE (K)


MIXING RATIO (g/kg)
0
10
20
30
40
50
ALTITUDE (km)
0
1
2
3
4
JULY 25
RUN
JULY 28
280
290
300
310
320
330
POTENTIAL TEMPERATURE (K)


MIXING RATIO (g/kg)
0
10
20
30
40
50
ALTITUDE (km)
0
1
2
3
4
JULY 29
JULY 30
280
290
300
310
320
330
POTENTIAL TEMPERATURE (K)


MIXING RATIO (g/kg)
0
10
20
30
40
50
ALTITUDE (km)
0
1
2
3
4
JULY 31
AUG 2
280
290
300
310
320
330
POTENTIAL TEMPERATURE (K)


MIXING RATIO (g/kg)
0
10
20
30
40
50
ALTITUDE (km)
0
1
2
3
4
AUG 3
AUG 4
280
290
300
310
320
330
POTENTIAL TEMPERATURE (K)


MIXING RATIO (g/kg)
0
10
20
30
40
50
ALTITUDE (km)
4
3
2
1
0
AUG 5

# OKLAHOMA CITY RAWINSONDE DATA

```
                MONTH  7   DAY 21   HOUR  600 CST
 P (MB)    Z (M)     T (C)    MIX R    PT (K)        WIND (M/S)
  971.0     392.      23.3     16.1     299.0        160/ 3
  952.0     565.      25.3     17.9     302.7        202/ 8
  950.0     584.      25.3     17.7     302.9        202/ 8
  931.0     762.      25.8     15.9     305.1        215/10
  900.0    1061.      24.9     14.7     307.2        229/ 8
  898.0    1085.      24.8     14.4     307.3        228/ 8
  850.0    1561.      21.8     12.4     309.0        231/ 2
  800.0    2085.      17.6     10.4     309.9         79/ 2
  750.0    2634.      13.1      8.7     310.8         62/ 5
  749.0    2645.      13.0      8.8     310.8         60/ 5
  736.0    2792.      11.3      9.0     310.5         53/ 6
  700.0    3215.       8.5      6.7     311.9         36/ 4
  655.0    3757.       5.0      6.3     313.9          4/ 2
  650.0    3825.       4.3      7.2     313.8        360/ 1
  647.0    3857.       3.8      7.8     313.6          1/ 1
  627.0    4112.       1.9      7.0     314.3         57/ 1
  605.0    4405.       0.8      3.8     316.3        107/ 1
  600.0    4467.       0.4      4.0     316.5        107/ 1
  594.0    4547.      -0.1      4.4     316.9        107/ 1
  580.0    4738.      -1.0      3.2     318.0          2/ 1
```

```
                MONTH  7   DAY 21   HOUR 1800 CST
 P (MB)    Z (M)     T (C)    MIX R    PT (K)        WIND (M/S)
  971.0     392.      29.4     16.2     305.1        170/ 6
  957.0     523.      27.2     15.4     304.2        164/ 6
  950.0     588.      26.6     15.2     304.2        163/ 6
  932.0     757.      25.0     15.1     304.2        157/ 6
  900.0    1065.      25.5     14.3     307.8        146/ 4
  850.0    1566.      22.2     11.1     309.4         93/ 3
  800.0    2091.      18.4      8.1     310.8         77/ 6
  750.0    2641.      14.4      5.6     312.2         57/ 8
  709.0    3112.      10.8      3.8     313.3         34/ 8
  700.0    3218.       9.1      6.8     312.5         35/ 8
  670.0    3585.       6.6      6.9     313.7         43/ 8
  661.0    3691.       6.6      3.4     314.9         44/ 8
  652.0    3803.       6.6      2.2     316.1         46/ 8
  650.0    3828.       6.5      2.2     316.3         46/ 8
  600.0    4479.       1.8      1.7     318.2         43/ 9
  564.0    4974.      -1.7      1.4     319.7         46/ 8
  550.0    5174.      -3.0      2.8     320.5         46/ 8
  548.0    5202.      -3.1      3.1     320.7         45/ 8
  540.0    5318.      -3.5      4.1     321.6         42/ 9
  529.0    5485.      -4.8      3.5     321.9         39/ 9
```

# OKLAHOMA CITY RAWINSONDE DATA

MONTH 7 DAY 22 HOUR 600 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 972.0 | 392. | 22.2 | 14.8 | 297.7 | 20/ 2 |
| 954.0 | 558. | 24.6 | 16.3 | 301.8 | 25/ 3 |
| 950.0 | 595. | 24.5 | 16.0 | 302.1 | 25/ 4 |
| 900.0 | 1075. | 22.9 | 11.0 | 305.1 | 357/ 2 |
| 889.0 | 1176. | 22.5 | 9.6 | 305.8 | 336/ 2 |
| 850.0 | 1564. | 18.6 | 11.7 | 305.6 | 340/ 2 |
| 803.0 | 2055. | 14.9 | 11.3 | 306.7 | 0/ 0 |
| 800.0 | 2082. | 14.9 | 10.9 | 307.0 | 0/ 0 |
| 770.0 | 2405. | 13.8 | 6.0 | 309.2 | 108/ 1 |
| 750.0 | 2626. | 12.0 | 7.7 | 309.6 | 94/ 2 |
| 732.0 | 2835. | 10.2 | 9.0 | 309.8 | 84/ 2 |
| 700.0 | 3201. | 8.3 | 5.8 | 311.7 | 83/ 1 |
| 673.0 | 3525. | 5.0 | 6.4 | 311.5 | 100/ 1 |
| 654.0 | 3759. | 4.2 | 5.6 | 313.1 | 100/ 1 |
| 650.0 | 3809. | 4.0 | 5.5 | 313.5 | 120/ 1 |
| 616.0 | 4244. | 1.3 | 5.3 | 315.2 | 78/ 2 |
| 600.0 | 4456. | 0.5 | 3.1 | 316.7 | 81/ 3 |
| 590.0 | 4591. | 0.0 | 1.6 | 317.6 | 86/ 3 |
| 573.0 | 4825. | -0.7 | 3.9 | 319.4 | 97/ 2 |
| 550.0 | 5152. | -2.0 | 2.5 | 321.7 | 115/ 1 |

MONTH 7 DAY 22 HOUR 1800 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 970.0 | 392. | 32.8 | 15.8 | 308.6 | 360/ 5 |
| 956.0 | 525. | 30.8 | 13.6 | 307.9 | 360/ 4 |
| 950.0 | 582. | 30.4 | 13.4 | 308.0 | 1/ 4 |
| 900.0 | 1065. | 26.2 | 12.7 | 308.5 | 338/ 2 |
| 850.0 | 1563. | 21.7 | 11.8 | 308.9 | 229/ 2 |
| 800.0 | 2086. | 17.0 | 11.7 | 309.3 | 214/ 4 |
| 759.0 | 2533. | 12.8 | 11.2 | 309.4 | 199/ 3 |
| 750.0 | 2633. | 12.1 | 10.6 | 309.7 | 200/ 3 |
| 712.0 | 3068. | 8.9 | 8.1 | 310.8 | 137/ 1 |
| 700.0 | 3209. | 8.9 | 7.4 | 312.3 | 119/ 2 |
| 665.0 | 3633. | 7.5 | 3.0 | 315.4 | 132/ 2 |
| 650.0 | 3821. | 6.4 | 2.3 | 316.2 | 142/ 2 |
| 645.0 | 3884. | 6.0 | 2.0 | 316.4 | 145/ 2 |
| 600.0 | 4472. | 1.8 | 3.6 | 318.2 | 137/ 3 |
| 592.0 | 4585. | 1.0 | 2.7 | 318.5 | 127/ 3 |
| 584.0 | 4689. | 0.2 | 2.7 | 318.8 | 115/ 3 |
| 575.0 | 4813. | -0.5 | 3.7 | 319.4 | 104/ 3 |
| 567.0 | 4925. | -1.3 | 3.1 | 319.7 | 101/ 3 |
| 557.0 | 5067. | -1.4 | 2.3 | 321.2 | 97/ 3 |
| 550.0 | 5168. | -2.0 | 2.5 | 321.7 | 98/ 3 |

# OKLAHOMA CITY RAWINSONDE DATA

MONTH 7 DAY 23 HOUR 600 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 972.0 | 392. | 21.7 | 14.7 | 297.3 | 170/ 2 |
| 965.0 | 455. | 25.9 | 15.6 | 302.1 | 180/ 3 |
| 950.0 | 594. | 25.6 | 15.1 | 303.2 | 188/ 4 |
| 910.0 | 973. | 24.7 | 13.2 | 306.0 | 220/ 5 |
| 900.0 | 1075. | 24.1 | 12.9 | 306.3 | 226/ 4 |
| 850.0 | 1568. | 20.6 | 11.5 | 307.7 | 274/ 2 |
| 800.0 | 2091. | 16.9 | 9.7 | 309.2 | 273/ 3 |
| 750.0 | 2639. | 12.9 | 8.1 | 310.6 | 287/ 6 |
| 700.0 | 3214. | 8.6 | 6.6 | 312.0 | 286/ 4 |
| 650.0 | 3823. | 4.3 | 6.6 | 313.8 | 291/ 3 |
| 648.0 | 3849. | 4.1 | 6.6 | 313.9 | 293/ 3 |
| 644.0 | 3899. | 3.9 | 4.3 | 314.2 | 299/ 3 |
| 635.0 | 4013. | 3.4 | 4.9 | 314.9 | 308/ 2 |
| 621.0 | 4194. | 2.4 | 3.5 | 315.7 | 336/ 2 |
| 605.0 | 4405. | 1.1 | 5.0 | 316.6 | 360/ 1 |
| 600.0 | 4472. | 0.8 | 4.0 | 317.0 | 2/ 1 |
| 593.0 | 4566. | 0.3 | 2.6 | 317.5 | 165/ 1 |
| 561.0 | 5009. | -2.6 | 4.8 | 319.1 | 188/ 2 |
| 553.0 | 5123. | -3.6 | 3.1 | 319.3 | 199/ 1 |
| 550.0 | 5166. | -3.7 | 3.4 | 319.7 | 203/ 1 |

MONTH 7 DAY 23 HOUR 1800 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 969.0 | 392. | 36.8 | 13.2 | 312.8 | 180/ 3 |
| 958.0 | 494. | 35.0 | 12.4 | 312.0 | 203/ 4 |
| 950.0 | 575. | 33.4 | 11.8 | 311.1 | 215/ 4 |
| 941.0 | 656. | 31.4 | 11.2 | 309.9 | 227/ 5 |
| 924.0 | 819. | 30.0 | 11.1 | 310.1 | 235/ 6 |
| 900.0 | 1054. | 28.1 | 11.0 | 310.5 | 238/ 6 |
| 850.0 | 1557. | 23.9 | 10.6 | 311.2 | 251/ 4 |
| 800.0 | 2083. | 18.4 | 10.0 | 310.8 | 260/ 4 |
| 775.0 | 2354. | 15.4 | 9.5 | 310.4 | 268/ 4 |
| 750.0 | 2632. | 13.5 | 9.6 | 311.2 | 291/ 4 |
| 740.0 | 2745. | 12.7 | 9.7 | 311.5 | 292/ 4 |
| 700.0 | 3211. | 10.6 | 7.4 | 314.2 | 275/ 5 |
| 692.0 | 3307. | 9.8 | 6.3 | 314.3 | 275/ 4 |
| 650.0 | 3825. | 5.8 | 6.6 | 315.5 | 300/ 4 |
| 628.0 | 4106. | 3.6 | 6.7 | 316.1 | 318/ 3 |
| 600.0 | 4476. | 1.3 | 6.3 | 317.6 | 319/ 3 |
| 591.0 | 4597. | 0.5 | 6.3 | 318.0 | 327/ 3 |
| 576.0 | 4803. | -1.0 | 5.7 | 318.6 | 332/ 2 |
| 560.0 | 5028. | -1.6 | 4.0 | 320.5 | 330/ 2 |
| 552.0 | 5143. | -1.6 | 5.7 | 321.8 | 323/ 1 |

# OKLAHOMA CITY RAWINSONDE DATA

## MONTH 7 DAY 24 HOUR 600 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 969.0 | 392. | 23.9 | 14.9 | 299.8 | 170/ 3 |
| 950.0 | 564. | 25.2 | 14.3 | 302.8 | 196/ 7 |
| 919.0 | 858. | 27.5 | 12.4 | 308.0 | 221/11 |
| 900.0 | 1044. | 26.5 | 12.2 | 308.8 | 229/13 |
| 850.0 | 1546. | 23.6 | 11.5 | 310.9 | 231/12 |
| 800.0 | 2073. | 19.3 | 10.9 | 311.7 | 245/ 7 |
| 750.0 | 2624. | 14.6 | 10.0 | 312.4 | 263/ 5 |
| 712.0 | 3062. | 10.8 | 9.2 | 312.9 | 322/ 2 |
| 700.0 | 3204. | 9.5 | 7.0 | 313.0 | 353/ 2 |
| 680.0 | 3444. | 7.7 | 7.4 | 313.6 | 9/ 1 |
| 666.0 | 3616. | 7.4 | 4.0 | 315.1 | 346/ 1 |
| 650.0 | 3816. | 5.5 | 5.1 | 315.2 | 303/ 2 |
| 643.0 | 3904. | 4.6 | 5.6 | 315.1 | 290/ 2 |
| 629.0 | 4083. | 4.1 | 3.8 | 316.5 | 276/ 3 |
| 617.0 | 4239. | 2.2 | 6.1 | 316.1 | 270/ 3 |
| 600.0 | 4464. | 0.6 | 5.9 | 316.8 | 260/ 2 |
| 576.0 | 4791. | -1.8 | 5.4 | 317.7 | 147/ 1 |
| 550.0 | 5158. | -2.5 | 4.2 | 321.1 | 140/ 2 |
| 542.0 | 5275. | -2.8 | 3.8 | 322.1 | 143/ 2 |
| 513.0 | 5709. | -5.5 | 1.8 | 323.9 | 192/ 1 |

## MONTH 7 DAY 24 HOUR 1800 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 965.0 | 392. | 39.4 | 11.9 | 315.7 | 210/ 5 |
| 951.0 | 527. | 35.9 | 12.8 | 313.5 | 209/ 5 |
| 950.0 | 537. | 35.9 | 12.8 | 313.6 | 209/ 5 |
| 900.0 | 1028. | 31.4 | 11.4 | 313.9 | 215/ 7 |
| 850.0 | 1535. | 26.7 | 10.2 | 314.1 | 211/ 5 |
| 800.0 | 2067. | 21.4 | 9.8 | 314.0 | 204/ 5 |
| 750.0 | 2622. | 15.7 | 8.8 | 313.6 | 211/ 6 |
| 749.0 | 2632. | 15.5 | 8.8 | 313.5 | 212/ 6 |
| 700.0 | 3202. | 10.8 | 9.0 | 314.4 | 235/ 6 |
| 676.0 | 3493. | 9.4 | 6.5 | 316.0 | 255/ 5 |
| 650.0 | 3818. | 7.1 | 5.7 | 317.0 | 267/ 6 |
| 603.0 | 4435. | 2.6 | 4.3 | 318.6 | 242/ 3 |
| 600.0 | 4475. | 2.3 | 4.2 | 318.7 | 240/ 3 |
| 582.0 | 4716. | 0.4 | 4.2 | 319.3 | 231/ 2 |
| 561.0 | 5015. | -1.7 | 4.4 | 320.2 | 0/ 0 |
| 550.0 | 5168. | -1.7 | 3.0 | 322.0 | 253/ 1 |
| 549.0 | 5182. | -1.7 | 2.8 | 322.2 | 253/ 1 |
| 524.0 | 5553. | -2.0 | 1.4 | 326.1 | 231/ 4 |
| 500.0 | 5924. | -4.5 | 1.2 | 327.5 | 237/ 3 |
| 473.0 | 6365. | -5.6 | 1.0 | 331.4 | 271/ 3 |

# OKLAHOMA CITY RAWINSONDE DATA

MONTH 7 DAY 25 HOUR 600 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 967.0 | 392. | 25.0 | 14.1 | 301.0 | 180/ 3 |
| 950.0 | 551. | 27.2 | 14.7 | 304.8 | 215/ 6 |
| 946.0 | 588. | 27.8 | 14.8 | 305.8 | 221/ 8 |
| 903.0 | 1002. | 29.1 | 13.7 | 311.2 | 240/13 |
| 900.0 | 1032. | 28.9 | 13.5 | 311.3 | 240/13 |
| 850.0 | 1537. | 24.4 | 11.6 | 311.7 | 245/10 |
| 800.0 | 2066. | 20.3 | 10.1 | 312.8 | 254/ 7 |
| 750.0 | 2619. | 15.9 | 8.6 | 313.8 | 272/ 5 |
| 700.0 | 3201. | 11.2 | 7.2 | 314.9 | 259/ 1 |
| 650.0 | 3816. | 6.3 | 5.5 | 316.1 | 343/ 1 |
| 616.0 | 4253. | 2.6 | 4.3 | 316.7 | 345/ 1 |
| 600.0 | 4465. | 0.8 | 4.4 | 317.0 | 0/ 0 |
| 581.0 | 4723. | -1.5 | 4.5 | 317.3 | 0/ 0 |
| 569.0 | 4889. | -3.3 | 3.8 | 317.0 | 285/ 1 |
| 561.0 | 5001. | -2.2 | 2.4 | 319.6 | 285/ 1 |
| 550.0 | 5158. | -2.2 | 2.0 | 321.4 | 280/ 1 |
| 537.0 | 5348. | -2.2 | 1.4 | 323.6 | 261/ 1 |
| 500.0 | 5912. | -5.1 | 1.1 | 326.8 | 266/ 3 |
| 456.0 | 6631. | -8.5 | 0.9 | 331.2 | 281/ 4 |
| 450.0 | 6734. | -9.2 | 0.8 | 331.6 | 278/ 3 |

MONTH 7 DAY 25 HOUR 1800 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 967.0 | 392. | 40.0 | 12.3 | 316.2 | 270/ 2 |
| 959.0 | 464. | 37.5 | 13.5 | 314.4 | 262/ 1 |
| 950.0 | 551. | 36.7 | 13.0 | 314.4 | 253/ 1 |
| 900.0 | 1044. | 31.8 | 11.7 | 314.3 | 207/ 2 |
| 850.0 | 1555. | 26.5 | 10.3 | 313.9 | 203/ 3 |
| 800.0 | 2082. | 21.7 | 10.2 | 314.3 | 209/ 2 |
| 750.0 | 2637. | 16.5 | 9.7 | 314.5 | 237/ 3 |
| 718.0 | 3006. | 12.9 | 9.1 | 314.5 | 247/ 4 |
| 700.0 | 3225. | 12.2 | 7.2 | 316.0 | 271/ 5 |
| 650.0 | 3836. | 7.7 | 6.4 | 317.6 | 296/ 5 |
| 600.0 | 4495. | 2.7 | 5.6 | 319.2 | 301/ 4 |
| 550.0 | 5188. | -2.5 | 4.6 | 321.1 | 320/ 4 |
| 540.0 | 5336. | -3.7 | 4.3 | 321.3 | 328/ 4 |
| 528.0 | 5514. | -1.8 | 1.3 | 325.7 | 339/ 3 |
| 500.0 | 5946. | -3.8 | 1.1 | 328.4 | 337/ 3 |
| 450.0 | 6769. | -9.0 | 0.7 | 331.9 | 296/ 5 |
| 434.0 | 7048. | -11.0 | 0.6 | 332.8 | 293/ 6 |
| 400.0 | 7669. | -16.0 | 0.5 | 334.1 | 300/ 5 |
| 350.0 | 8664. | -22.7 | 0.3 | 338.1 | 281/ 2 |
| 331.0 | 9068. | -25.5 | 0.2 | 339.7 | 256/ 2 |

## OKLAHOMA CITY  RAWINSONDE DATA

```
                 MONTH  7   DAY 28   HOUR  600 CST
 P (MB)      Z (M)      T (C)     MIX R    PT (K)       WIND (M/S)
  970.0       392.       22.2      16.2     297.9       110/ 2
  950.0       575.       21.1      14.6     298.6       999/**
  930.0       765.       20.7      14.1     300.0       999/**
  900.0      1045.       20.5      14.7     302.6       999/**
  898.0      1064.       20.4      14.8     302.7       999/**
  865.0      1387.       17.9      13.1     303.4       999/**
  850.0      1537.       16.8      12.5     303.7       999/**
  831.0      1735.       15.0      11.3     303.8       999/**
  823.0      1812.       13.8      10.6     303.4       999/**
  819.0      1853.       16.2      12.5     306.3       999/**
  800.0      2053.       16.7       7.6     308.9       999/**
  799.0      2064.       16.8       7.2     309.2       999/**
  750.0      2605.       13.0       6.8     310.7       999/**
  740.0      2713.       12.1       6.8     310.9       999/**
  700.0      3177.        8.9       6.0     312.3       999/**
  694.0      3248.        8.5       4.6     312.6       999/**
  680.0      3417.        9.1       2.0     315.1       999/**
  650.0      3789.        7.1       1.9     317.0       999/**
  644.0      3865.        6.6       1.8     317.2       999/**
  600.0      4442.        3.2       1.5     319.8       999/**


                 MONTH  7   DAY 28   HOUR 1800 CST
 P (MB)      Z (M)      T (C)     MIX R    PT (K)       WIND (M/S)
  968.0       392.       32.2      17.6     308.2       180/ 2
  952.0       544.       30.4      17.5     307.9       180/ 1
  950.0       563.       30.3      17.5     307.9       180/ 1
  900.0      1045.       26.1      17.2     308.4       227/ 1
  879.0      1253.       24.2      17.0     308.5       243/ 1
  850.0      1547.       21.5      14.9     308.7       264/ 1
  814.0      1922.       18.7      12.7     309.5       283/ 1
  800.0      2071.       17.9      10.2     310.2       285/ 2
  762.0      2486.       15.6       3.4     312.1       284/ 5
  750.0      2621.       15.0       3.5     312.8       289/ 4
  700.0      3201.       11.9       3.9     315.6       333/ 1
  650.0      3816.        7.4       3.2     317.3        21/ 4
  600.0      4469.        2.5       2.5     319.0         6/ 7
  592.0      4577.        1.6       2.5     319.2       360/ 6
  550.0      5167.       -1.4       1.9     322.4       330/ 6
  523.0      5566.       -3.6       1.5     324.4       308/ 9
  500.0      5925.       -6.1       3.1     325.5       297/ 9
  496.0      5983.       -6.4       2.7     325.9       294/ 9
  453.0      6087.      -10.8       1.9     329.0       276/ 8
  450.0      6736.      -11.0       1.9     329.3       276/ 8
```

# OKLAHOMA CITY RAWINSONDE DATA

MONTH 7 DAY 29 HOUR 600 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 970.0 | 392. | 22.8 | 14.3 | 298.5 | 340/ 4 |
| 959.0 | 494. | 24.7 | 15.0 | 301.4 | 356/ 5 |
| 950.0 | 577. | 24.3 | 13.2 | 301.9 | 2/ 5 |
| 946.0 | 614. | 24.0 | 12.0 | 301.9 | 8/ 5 |
| 900.0 | 1055. | 22.7 | 10.4 | 304.9 | 353/ 1 |
| 850.0 | 1546. | 21.0 | 8.4 | 308.1 | 271/ 2 |
| 800.0 | 2068. | 17.3 | 7.2 | 309.6 | 202/ 3 |
| 750.0 | 2615. | 13.3 | 6.2 | 311.0 | 181/ 4 |
| 710.0 | 3073. | 9.8 | 5.4 | 312.0 | 167/ 5 |
| 700.0 | 3191. | 9.3 | 5.3 | 312.8 | 166/ 5 |
| 650.0 | 3802. | 5.0 | 4.1 | 314.6 | 75/ 1 |
| 642.0 | 3902. | 4.2 | 3.9 | 314.8 | 26/ 1 |
| 614.0 | 4263. | 0.9 | 5.0 | 315.0 | 340/ 4 |
| 600.0 | 4448. | 0.0 | 4.7 | 316.1 | 333/ 5 |
| 599.0 | 4462. | -0.1 | 4.6 | 316.1 | 332/ 5 |
| 588.0 | 4611. | 1.2 | 2.1 | 319.3 | 333/ 6 |
| 574.0 | 4804. | 0.0 | 2.2 | 320.1 | 339/ 7 |
| 550.0 | 5145. | -2.6 | 4.3 | 321.0 | 342/ 3 |
| 539.0 | 5305. | -4.0 | 5.0 | 321.1 | 342/ 1 |
| 528.0 | 5468. | -5.0 | 4.6 | 321.8 | 273/ 1 |

MONTH 7 DAY 29 HOUR 1800 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 968.0 | 392. | 33.9 | 15.8 | 309.9 | 340/ 4 |
| 950.0 | 563. | 30.8 | 13.7 | 308.4 | 331/ 3 |
| 908.0 | 966. | 27.0 | 13.5 | 308.6 | 337/ 2 |
| 900.0 | 1044. | 26.3 | 13.5 | 308.6 | 341/ 2 |
| 850.0 | 1545. | 21.3 | 13.0 | 308.5 | 6/ 1 |
| 823.0 | 1824. | 18.6 | 13.5 | 308.5 | 34/ 1 |
| 800.0 | 2067. | 17.1 | 11.8 | 309.4 | 11/ 1 |
| 750.0 | 2616. | 13.7 | 8.6 | 311.4 | 340/ 2 |
| 729.0 | 2855. | 12.1 | 7.2 | 312.2 | 328/ 3 |
| 700.0 | 3194. | 9.9 | 4.7 | 313.4 | 308/ 4 |
| 679.0 | 3446. | 8.7 | 2.2 | 314.8 | 311/ 4 |
| 650.0 | 3805. | 6.4 | 2.0 | 316.2 | 322/ 3 |
| 600.0 | 4456. | 2.2 | 1.5 | 318.6 | 342/ 5 |
| 565.0 | 4938. | -1.0 | 1.2 | 320.4 | 356/ 4 |
| 550.0 | 5153. | -1.0 | 1.2 | 322.9 | 354/ 4 |
| 545.0 | 5225. | -1.0 | 1.2 | 323.7 | 352/ 5 |
| 500.0 | 5906. | -5.7 | 0.9 | 326.0 | 351/ 6 |
| 474.0 | 6323. | -7.6 | 0.8 | 328.7 | 356/ 3 |
| 450.0 | 6725. | -10.6 | 0.6 | 329.8 | 345/ 2 |
| 437.0 | 6955. | -12.3 | 0.6 | 330.5 | 340/ 3 |

# OKLAHOMA CITY RAWINSONDE DATA

MONTH 7 DAY 30 HOUR 600 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 968.0 | 392. | 22.2 | 15.9 | 298.1 | 170/ 4 |
| 950.0 | 558. | 24.9 | 15.1 | 302.5 | 207/ 5 |
| 940.0 | 652. | 26.5 | 14.3 | 305.0 | 223/ 6 |
| 900.0 | 1036. | 24.2 | 12.3 | 306.4 | 223/ 7 |
| 850.0 | 1534. | 21.1 | 9.6 | 308.2 | 217/ 4 |
| 800.0 | 2055. | 16.0 | 9.4 | 308.2 | 226/ 3 |
| 753.0 | 2566. | 10.8 | 8.6 | 307.9 | 211/ 4 |
| 750.0 | 2599. | 10.7 | 8.1 | 308.2 | 211/ 4 |
| 733.0 | 2795. | 9.7 | 4.8 | 309.1 | 217/ 5 |
| 700.0 | 3172. | 8.2 | 2.1 | 311.5 | 223/ 7 |
| 676.0 | 3465. | 8.8 | 2.0 | 315.3 | 226/ 4 |
| 650.0 | 3783. | 6.9 | 1.8 | 316.7 | 230/ 4 |
| 600.0 | 4436. | 3.0 | 1.5 | 319.6 | 277/ 1 |
| 550.0 | 5135. | -1.1 | 1.2 | 322.7 | 0/ 0 |
| 531.0 | 5414. | -3.0 | 1.1 | 323.7 | 332/ 1 |
| 500.0 | 5886. | -7.3 | 0.8 | 324.1 | 328/ 1 |
| 450.0 | 6697. | -13.3 | 0.5 | 326.5 | 309/ 4 |
| 400.0 | 7581. | -20.2 | 0.3 | 328.7 | 272/ 6 |
| 368.0 | 8193. | -24.5 | 0.2 | 330.9 | 307/ 6 |
| 350.0 | 8565. | -26.2 | 0.2 | 333.3 | 318/12 |

MONTH 7 DAY 30 HOUR 1800 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 964.0 | 392. | 35.6 | 19.2 | 312.0 | 200/ 4 |
| 951.0 | 519. | 33.2 | 12.7 | 310.8 | 200/ 5 |
| 950.0 | 529. | 33.2 | 12.7 | 310.9 | 200/ 5 |
| 900.0 | 1015. | 28.7 | 11.4 | 311.1 | 218/ 6 |
| 850.0 | 1518. | 23.9 | 10.1 | 311.2 | 225/ 6 |
| 800.0 | 2044. | 18.6 | 9.8 | 311.0 | 235/ 7 |
| 794.0 | 2108. | 17.9 | 9.7 | 310.9 | 237/ 6 |
| 786.0 | 2195. | 18.1 | 7.4 | 312.0 | 240/ 6 |
| 753.0 | 2561. | 15.8 | 5.0 | 313.4 | 270/ 3 |
| 750.0 | 2595. | 15.6 | 5.0 | 313.5 | 275/ 3 |
| 700.0 | 3175. | 10.8 | 5.3 | 314.4 | 310/ 4 |
| 672.0 | 3514. | 8.1 | 4.0 | 315.1 | 330/ 7 |
| 650.0 | 3789. | 9.3 | 2.4 | 319.5 | 344/10 |
| 648.0 | 3815. | 9.5 | 2.2 | 320.0 | 346/10 |
| 600.0 | 4447. | 4.6 | 2.5 | 321.4 | 348/11 |
| 590.0 | 4584. | 3.5 | 2.5 | 321.7 | 344/10 |
| 550.0 | 5149. | -1.1 | 1.5 | 322.7 | 330/ 8 |
| 543.0 | 5251. | -2.0 | 1.3 | 322.8 | 327/ 8 |
| 500.0 | 5902. | -5.4 | 1.2 | 326.4 | 307/11 |
| 450.0 | 6721. | -10.1 | 0.8 | 330.5 | 303/13 |

# OKLAHOMA CITY RAWINSONDE DATA

MONTH 7 DAY 31 HOUR 600 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 968.0 | 392. | 21.1 | 12.6 | 297.1 | 130/ 5 |
| 952.0 | 533. | 25.3 | 14.0 | 302.7 | 136/10 |
| 950.0 | 552. | 25.3 | 14.0 | 302.9 | 136/10 |
| 900.0 | 1027. | 23.8 | 13.5 | 306.0 | 169/10 |
| 889.0 | 1135. | 23.4 | 13.3 | 306.7 | 185/10 |
| 864.0 | 1384. | 21.2 | 12.7 | 306.9 | 211/10 |
| 850.0 | 1526. | 22.3 | 12.4 | 309.5 | 221/11 |
| 800.0 | 2052. | 18.4 | 10.3 | 310.8 | 242/11 |
| 750.0 | 2602. | 14.1 | 8.3 | 311.9 | 253/ 8 |
| 749.0 | 2612. | 14.0 | 8.3 | 311.9 | 254/ 8 |
| 700.0 | 3179. | 9.5 | 8.5 | 313.0 | 291/ 8 |
| 662.0 | 3641. | 6.6 | 8.6 | 314.8 | 326/ 9 |
| 650.0 | 3791. | 5.5 | 7.5 | 315.2 | 334/10 |
| 619.0 | 4195. | 2.5 | 4.9 | 316.1 | 341/10 |
| 605.0 | 4375. | 0.7 | 5.5 | 316.1 | 340/10 |
| 600.0 | 4442. | 0.3 | 5.2 | 316.4 | 340/10 |
| 592.0 | 4549. | -0.3 | 4.6 | 316.9 | 340/10 |
| 580.0 | 4712. | -2.2 | 4.4 | 316.6 | 340/10 |
| 550.0 | 5133. | -4.0 | 1.6 | 319.3 | 337/11 |
| 548.0 | 5161. | -4.2 | 1.4 | 319.4 | 336/11 |

MONTH 7 DAY 31 HOUR 1800 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 968.0 | 392. | 30.6 | 13.0 | 306.6 | 80/ 7 |
| 960.0 | 464. | 29.0 | 12.5 | 305.7 | 76/ 9 |
| 950.0 | 557. | 28.6 | 12.3 | 306.2 | 74/11 |
| 900.0 | 1036. | 26.0 | 11.8 | 308.3 | 79/ 9 |
| 892.0 | 1115. | 25.5 | 11.8 | 308.6 | 81/ 9 |
| 871.0 | 1325. | 25.1 | 9.9 | 310.3 | 88/ 6 |
| 850.0 | 1539. | 23.2 | 9.7 | 310.4 | 109/ 4 |
| 839.0 | 1652. | 21.6 | 9.3 | 309.9 | 131/ 3 |
| 818.0 | 1872. | 21.4 | 8.2 | 312.0 | 182/ 5 |
| 800.0 | 2065. | 20.0 | 7.9 | 312.5 | 189/ 6 |
| 750.0 | 2618. | 15.6 | 7.1 | 313.5 | 188/ 8 |
| 700.0 | 3198. | 10.9 | 6.3 | 314.5 | 222/ 7 |
| 650.0 | 3812. | 6.2 | 6.6 | 315.9 | 294/ 7 |
| 643.0 | 3901. | 5.5 | 6.6 | 316.1 | 297/ 7 |
| 615.0 | 4264. | 2.8 | 6.5 | 317.1 | 292/ 7 |
| 600.0 | 4463. | -0.2 | 4.8 | 315.9 | 273/ 9 |
| 587.0 | 4638. | -1.8 | 3.7 | 316.0 | 262/15 |
| 583.0 | 4692. | -0.8 | 4.3 | 317.8 | 269/16 |
| 550.0 | 5156. | -3.4 | 3.3 | 320.0 | 287/19 |
| 548.0 | 5184. | -3.6 | 3.2 | 320.1 | 289/19 |

# OKLAHOMA CITY RAWINSONDE DATA

MONTH 8 DAY 2 HOUR 600 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 972.0 | 392. | 22.2 | 15.2 | 297.8 | 360/ 5 |
| 958.0 | 518. | 23.4 | 15.6 | 300.2 | 336/ 5 |
| 950.0 | 592. | 23.0 | 15.4 | 300.5 | 328/ 5 |
| 903.0 | 1034. | 20.3 | 14.3 | 302.1 | 228/ 4 |
| 900.0 | 1063. | 20.1 | 14.2 | 302.2 | 228/ 4 |
| 850.0 | 1554. | 16.1 | 12.6 | 303.0 | 193/ 4 |
| 800.0 | 2069. | 13.0 | 9.1 | 305.0 | 224/ 3 |
| 792.0 | 2153. | 12.4 | 8.5 | 305.2 | 223/ 3 |
| 781.0 | 2275. | 11.8 | 10.3 | 305.8 | 223/ 3 |
| 754.0 | 2564. | 9.6 | 8.4 | 306.5 | 224/ 3 |
| 750.0 | 2608. | 9.5 | 8.3 | 306.9 | 224/ 3 |
| 720.0 | 2947. | 8.2 | 7.0 | 309.0 | 228/ 3 |
| 700.0 | 3179. | 6.9 | 4.3 | 310.1 | 242/ 5 |
| 689.0 | 3309. | 6.8 | 2.5 | 311.4 | 250/ 7 |
| 663.0 | 3625. | 6.4 | 2.7 | 314.4 | 264/10 |
| 650.0 | 3787. | 4.9 | 2.8 | 314.5 | 267/10 |
| 612.0 | 4274. | 0.1 | 2.8 | 314.4 | 280/11 |
| 600.0 | 4432. | -1.1 | 3.0 | 314.8 | 285/12 |
| 576.0 | 4756. | -4.0 | 3.1 | 315.1 | 302/12 |
| 556.0 | 5034. | -5.6 | 3.7 | 316.4 | 312/14 |

MONTH 8 DAY 2 HOUR 1800 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 969.0 | 392. | 33.3 | 12.5 | 309.2 | 190/ 3 |
| 950.0 | 572. | 30.4 | 15.8 | 308.0 | 124/ 3 |
| 930.0 | 762. | 28.8 | 11.3 | 308.3 | 97/ 4 |
| 900.0 | 1053. | 25.8 | 11.2 | 308.1 | 94/ 3 |
| 850.0 | 1552. | 20.5 | 10.5 | 307.6 | 59/ 1 |
| 800.0 | 2072. | 15.6 | 10.3 | 307.8 | 73/ 1 |
| 779.0 | 2298. | 13.4 | 10.1 | 307.8 | 349/ 1 |
| 750.0 | 2617. | 11.6 | 7.3 | 309.2 | 352/ 2 |
| 744.0 | 2684. | 11.2 | 6.7 | 309.4 | 352/ 2 |
| 700.0 | 3191. | 7.9 | 6.0 | 311.2 | 343/ 6 |
| 665.0 | 3612. | 4.9 | 5.4 | 312.4 | 324/ 7 |
| 650.0 | 3798. | 3.8 | 4.3 | 313.2 | 323/ 8 |
| 608.0 | 4338. | 0.5 | 1.4 | 315.5 | 335/10 |
| 600.0 | 4444. | -0.1 | 1.3 | 316.0 | 338/10 |
| 550.0 | 5134. | -5.0 | 1.1 | 318.1 | 349/11 |
| 506.0 | 5783. | -9.8 | 1.0 | 319.9 | 338/11 |
| 500.0 | 5875. | -9.5 | 0.7 | 321.4 | 337/12 |
| 496.0 | 5937. | -9.3 | 0.7 | 322.4 | 336/13 |
| 463.0 | 6465. | -13.6 | 0.5 | 323.4 | 338/18 |
| 455.0 | 6598. | -13.6 | 0.5 | 325.0 | 336/21 |

## OKLAHOMA CITY RAWINSONDE DATA

MONTH 8 DAY 3 HOUR 600 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 970.0 | 392. | 21.7 | 15.4 | 297.5 | 150/ 3 |
| 961.0 | 469. | 24.4 | 16.3 | 301.0 | 173/ 4 |
| 950.0 | 575. | 24.7 | 14.3 | 302.3 | 191/ 6 |
| 947.0 | 598. | 24.9 | 13.7 | 302.7 | 194/ 7 |
| 900.0 | 1044. | 23.7 | 10.3 | 305.9 | 207/ 6 |
| 871.0 | 1335. | 22.8 | 7.8 | 307.9 | 216/ 3 |
| 850.0 | 1542. | 21.0 | 7.1 | 308.1 | 234/ 2 |
| 800.0 | 2064. | 17.1 | 7.6 | 309.4 | 204/ 3 |
| 785.0 | 2224. | 15.8 | 7.7 | 309.7 | 192/ 3 |
| 752.0 | 2587. | 12.1 | 7.1 | 309.5 | 179/ 3 |
| 750.0 | 2609. | 12.0 | 7.1 | 309.6 | 179/ 3 |
| 717.0 | 2985. | 9.3 | 4.4 | 310.6 | 201/ 3 |
| 700.0 | 3184. | 8.2 | 3.0 | 311.5 | 249/ 2 |
| 684.0 | 3375. | 7.8 | 2.3 | 313.2 | 294/ 2 |
| 650.0 | 3793. | 4.7 | 2.0 | 314.3 | 322/ 6 |
| 640.0 | 3919. | 3.7 | 1.9 | 314.5 | 331/ 7 |
| 631.0 | 4034. | 3.5 | 1.9 | 315.6 | 336/ 8 |
| 600.0 | 4445. | -0.1 | 1.9 | 316.0 | 352/ 9 |
| 585.0 | 4642. | -2.1 | 1.9 | 315.9 | 356/ 8 |
| 568.0 | 4875. | -4.0 | 1.0 | 316.4 | 353/ 7 |

MONTH 8 DAY 3 HOUR 1800 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 968.0 | 392. | 34.4 | 16.3 | 310.5 | 210/ 5 |
| 950.0 | 557. | 31.2 | 12.2 | 308.9 | 197/ 6 |
| 900.0 | 1045. | 26.6 | 10.8 | 308.9 | 190/ 6 |
| 850.0 | 1539. | 21.7 | 9.4 | 308.9 | 185/ 6 |
| 800.0 | 2061. | 17.0 | 9.0 | 309.3 | 183/ 6 |
| 784.0 | 2233. | 15.4 | 8.8 | 309.3 | 184/ 6 |
| 750.0 | 2608. | 12.7 | 5.6 | 310.3 | 192/ 5 |
| 737.0 | 2754. | 11.5 | 4.3 | 310.6 | 197/ 3 |
| 700.0 | 3184. | 11.2 | 4.5 | 314.9 | 335/ 2 |
| 650.0 | 3797. | 6.3 | 4.3 | 316.1 | 317/ 9 |
| 600.0 | 4447. | 1.0 | 3.8 | 317.2 | 325/ 9 |
| 585.0 | 4651. | -0.6 | 3.7 | 317.7 | 333/ 9 |
| 568.0 | 4887. | -1.0 | 2.0 | 319.9 | 342/10 |
| 550.0 | 5143. | -2.5 | 1.9 | 321.1 | 341/11 |
| 500.0 | 5892. | -7.6 | 1.5 | 323.7 | 333/15 |
| 450.0 | 6703. | -13.1 | 0.9 | 326.7 | 335/11 |
| 400.0 | 7595. | -19.3 | 0.4 | 329.8 | 312/12 |
| 350.0 | 8569. | -27.7 | 0.2 | 331.3 | 301/14 |
| 317.0 | 9269. | -34.0 | 0.2 | 332.1 | 303/13 |
| 300.0 | 9652. | -37.8 | 0.2 | 332.0 | 303/14 |

# OKLAHOMA CITY RAWINSONDE DATA

MONTH 8 DAY 4 HOUR 600 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 968.0 | 392. | 22.8 | 12.7 | 298.7 | 170/ 5 |
| 959.0 | 472. | 23.3 | 12.6 | 300.0 | 178/ 8 |
| 950.0 | 554. | 23.3 | 12.6 | 300.8 | 183/12 |
| 942.0 | 628. | 23.3 | 12.3 | 301.6 | 186/16 |
| 932.0 | 722. | 25.1 | 11.0 | 304.3 | 188/20 |
| 900.0 | 1029. | 23.7 | 10.7 | 305.9 | 197/21 |
| 850.0 | 1527. | 21.4 | 10.2 | 308.6 | 208/14 |
| 800.0 | 2052. | 19.0 | 9.5 | 311.4 | 219/11 |
| 752.0 | 2581. | 16.5 | 8.9 | 314.2 | 251/ 9 |
| 750.0 | 2604. | 16.4 | 8.9 | 314.4 | 251/ 9 |
| 700.0 | 3187. | 11.7 | 8.1 | 315.4 | 285/ 5 |
| 650.0 | 3802. | 5.9 | 7.9 | 315.6 | 309/ 4 |
| 643.0 | 3891. | 5.0 | 7.9 | 315.6 | 310/ 5 |
| 636.0 | 3985. | 4.8 | 7.6 | 316.3 | 307/ 5 |
| 628.0 | 4084. | 5.5 | 4.0 | 318.3 | 303/ 4 |
| 623.0 | 4149. | 5.5 | 3.5 | 319.0 | 299/ 4 |
| 600.0 | 4456. | 3.4 | 3.1 | 320.0 | 309/ 2 |
| 552.0 | 5126. | -1.2 | 2.3 | 322.3 | 322/ 4 |
| 550.0 | 5155. | -1.4 | 2.2 | 322.4 | 321/ 4 |
| 519.0 | 5614. | -5.2 | 2.2 | 323.2 | 328/ 6 |

MONTH 8 DAY 4 HOUR 1800 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 966.0 | 392. | 34.4 | 14.9 | 310.7 | 160/ 9 |
| 950.0 | 538. | 30.7 | 11.5 | 308.3 | 164/10 |
| 908.0 | 941. | 27.3 | 10.9 | 308.9 | 171/11 |
| 904.0 | 985. | 26.6 | 10.5 | 308.5 | 172/11 |
| 900.0 | 1019. | 26.3 | 10.3 | 308.6 | 172/11 |
| 850.0 | 1519. | 21.1 | 10.4 | 308.2 | 178/11 |
| 815.0 | 1881. | 17.6 | 9.9 | 308.3 | 186/ 8 |
| 800.0 | 2045. | 17.1 | 8.5 | 309.4 | 194/ 8 |
| 765.0 | 2421. | 15.7 | 4.9 | 311.8 | 219/ 7 |
| 750.0 | 2589. | 15.6 | 5.4 | 313.5 | 231/ 7 |
| 746.0 | 2634. | 15.5 | 5.6 | 313.9 | 234/ 7 |
| 700.0 | 3175. | 11.6 | 5.1 | 315.3 | 284/ 7 |
| 679.0 | 3424. | 9.9 | 5.6 | 316.2 | 294/ 6 |
| 650.0 | 3787. | 9.0 | 3.9 | 319.1 | 301/ 6 |
| 642.0 | 3889. | 8.7 | 3.4 | 319.9 | 305/ 6 |
| 600.0 | 4445. | 4.2 | 3.3 | 320.9 | 330/ 8 |
| 550.0 | 5145. | -1.6 | 2.9 | 322.1 | 333/ 8 |
| 548.0 | 5173. | -2.0 | 2.8 | 322.0 | 332/ 8 |
| 500.0 | 5894. | -8.3 | 2.0 | 322.9 | 339/ 5 |
| 453.0 | 6653. | -13.3 | 1.1 | 325.8 | 320/ 7 |

MONTH 8 DAY 5 HOUR 600 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 969.0 | 392. | 23.3 | 14.4 | 299.1 | 170/ 4 |
| 966.0 | 421. | 23.5 | 14.4 | 299.6 | 177/ 6 |
| 950.0 | 567. | 24.6 | 14.0 | 302.2 | 183/11 |
| 933.0 | 727. | 25.8 | 13.3 | 304.9 | 191/15 |
| 900.0 | 1044. | 24.3 | 11.5 | 306.6 | 205/16 |
| 869.0 | 1355. | 22.8 | 9.9 | 308.1 | 223/12 |
| 850.0 | 1543. | 23.3 | 8.7 | 310.5 | 239/10 |
| 814.0 | 1925. | 22.4 | 6.9 | 313.5 | 264/ 7 |
| 800.0 | 2071. | 21.2 | 7.1 | 313.7 | 269/ 7 |
| 750.0 | 2626. | 16.4 | 7.3 | 314.4 | 273/ 6 |
| 700.0 | 3207. | 11.2 | 7.1 | 314.9 | 271/ 5 |
| 656.0 | 3746. | 7.2 | 6.9 | 316.2 | 229/ 3 |
| 650.0 | 3822. | 6.5 | 7.4 | 316.3 | 224/ 3 |
| 644.0 | 3898. | 5.6 | 7.8 | 316.1 | 213/ 3 |
| 600.0 | 4475. | 2.0 | 6.1 | 318.4 | 195/ 4 |
| 563.0 | 4986. | -1.3 | 4.7 | 320.4 | 200/ 6 |
| 550.0 | 5172. | -2.7 | 4.6 | 320.8 | 198/ 7 |
| 522.0 | 5584. | -6.1 | 4.4 | 321.6 | 212/ 4 |
| 507.0 | 5812. | -8.0 | 3.8 | 322.0 | 214/ 4 |
| 500.0 | 5925. | -8.5 | 2.9 | 322.6 | 210/ 4 |

MONTH 8 DAY 5 HOUR 1800 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 969.0 | 392. | 33.9 | 14.0 | 309.9 | 190/ 6 |
| 954.0 | 528. | 31.7 | 12.5 | 309.0 | 178/ 7 |
| 950.0 | 566. | 31.3 | 12.3 | 309.0 | 176/ 7 |
| 900.0 | 1047. | 25.8 | 10.5 | 308.1 | 166/10 |
| 850.0 | 1547. | 21.4 | 10.0 | 308.6 | 174/ 7 |
| 800.0 | 2068. | 16.5 | 9.4 | 308.7 | 186/ 8 |
| 772.0 | 2371. | 13.6 | 9.0 | 308.8 | 185/ 7 |
| 762.0 | 2481. | 13.4 | 5.5 | 309.7 | 180/ 6 |
| 752.0 | 2593. | 16.4 | 6.3 | 314.1 | 174/ 5 |
| 750.0 | 2616. | 16.3 | 6.3 | 314.3 | 174/ 5 |
| 700.0 | 3199. | 12.8 | 5.8 | 316.6 | 198/ 3 |
| 650.0 | 3817. | 7.8 | 5.8 | 317.8 | 338/ 1 |
| 600.0 | 4471. | 2.4 | 5.4 | 318.9 | 318/ 4 |
| 593.0 | 4566. | 1.6 | 5.4 | 319.0 | 312/ 4 |
| 550.0 | 5169. | -2.1 | 4.1 | 321.5 | 307/ 9 |
| 500.0 | 5925. | -7.1 | 2.7 | 324.3 | 313/ 7 |
| 450.0 | 6735. | -12.0 | 1.9 | 328.1 | 328/ 3 |
| 430.0 | 7081. | -14.1 | 1.6 | 329.7 | 301/ 1 |
| 400.0 | 7626. | -18.0 | 1.4 | 331.5 | 238/ 2 |
| 374.0 | 8126. | -20.8 | 0.7 | 334.2 | 253/ 3 |

# OKLAHOMA CITY RAWINSONDE DATA

MONTH 9 DAY 2 HOUR 600 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 974.0 | 392. | 18.9 | 12.7 | 294.2 | 180/ 2 |
| 959.0 | 535. | 25.4 | 15.9 | 302.2 | 190/ 6 |
| 950.0 | 613. | 24.9 | 15.4 | 302.5 | 191/ 9 |
| 915.0 | 943. | 22.8 | 13.2 | 303.6 | 191/10 |
| 900.0 | 1087. | 21.6 | 12.7 | 303.8 | 188/ 9 |
| 850.0 | 1585. | 17.4 | 10.9 | 304.4 | 199/ 7 |
| 800.0 | 2097. | 15.4 | 6.4 | 307.6 | 217/ 5 |
| 786.0 | 2246. | 14.8 | 5.2 | 308.5 | 225/ 5 |
| 750.0 | 2642. | 12.4 | 5.0 | 310.0 | 255/ 1 |
| 735.0 | 2815. | 11.3 | 5.0 | 310.6 | 309/ 1 |
| 700.0 | 3216. | 8.4 | 8.1 | 311.8 | 357/ 1 |
| 665.0 | 3639. | 6.6 | 3.7 | 314.3 | 109/ 2 |
| 650.0 | 3826. | 5.7 | 3.6 | 315.4 | 114/ 3 |
| 600.0 | 4477. | 2.3 | 3.0 | 318.7 | 154/ 2 |
| 569.0 | 4904. | 0.0 | 2.6 | 320.9 | 131/ 2 |
| 550.0 | 5175. | -2.4 | 2.2 | 321.2 | 165/ 1 |
| 545.0 | 5247. | -3.1 | 2.1 | 321.2 | 183/ 1 |
| 519.0 | 5633. | -4.8 | 1.2 | 323.7 | 179/ 3 |
| 500.0 | 5925. | -6.3 | 1.1 | 325.3 | 185/ 6 |
| 450.0 | 6743. | -10.0 | 0.7 | 330.6 | 184/ 3 |

MONTH 9 DAY 2 HOUR 1800 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 973.0 | 392. | 32.2 | 13.9 | 307.7 | 150/ 5 |
| 956.0 | 552. | 28.8 | 11.8 | 305.9 | 151/ 5 |
| 950.0 | 608. | 28.4 | 11.6 | 306.0 | 151/ 6 |
| 930.0 | 797. | 26.9 | 11.6 | 306.3 | 151/ 5 |
| 900.0 | 1086. | 24.3 | 11.3 | 306.6 | 152/ 4 |
| 850.0 | 1583. | 19.7 | 10.7 | 306.8 | 160/ 4 |
| 829.0 | 1798. | 18.2 | 7.7 | 307.4 | 146/ 4 |
| 800.0 | 2102. | 15.8 | 6.9 | 308.0 | 130/ 4 |
| 750.0 | 2646. | 11.4 | 5.5 | 308.9 | 158/ 2 |
| 711.0 | 3089. | 7.7 | 4.5 | 309.6 | 147/ 1 |
| 700.0 | 3218. | 7.5 | 3.7 | 310.8 | 133/ 1 |
| 672.0 | 3554. | 6.8 | 2.2 | 313.6 | 96/ 1 |
| 650.0 | 3827. | 6.3 | 2.2 | 316.1 | 47/ 1 |
| 646.0 | 3878. | 6.1 | 2.2 | 316.4 | 40/ 2 |
| 620.0 | 4213. | 3.8 | 3.1 | 317.5 | 37/ 2 |
| 600.0 | 4479. | 3.5 | 2.4 | 320.1 | 146/ 1 |
| 595.0 | 4547. | 3.3 | 2.1 | 320.7 | 146/ 1 |
| 550.0 | 5185. | 1.0 | 2.1 | 325.2 | 41/ 3 |
| 544.0 | 5267. | -1.6 | 1.8 | 323.2 | 41/ 3 |
| 500.0 | 5932. | -6.8 | 1.2 | 324.7 | 312/ 1 |

# OKLAHOMA CITY RAWINSONDE DATA

MONTH 9 DAY 3 HOUR 600 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 974.0 | 392. | 20.6 | 13.8 | 296.0 | 160/ 3 |
| 961.0 | 509. | 26.6 | 14.3 | 303.2 | 161/ 5 |
| 950.0 | 611. | 25.9 | 13.8 | 303.5 | 162/ 6 |
| 900.0 | 1086. | 22.1 | 11.7 | 304.3 | 167/ 6 |
| 850.0 | 1579. | 18.1 | 10.0 | 305.1 | 188/ 4 |
| 800.0 | 2095. | 14.2 | 9.1 | 306.3 | 0/ 0 |
| 791.0 | 2191. | 13.4 | 9.0 | 306.4 | 0/ 0 |
| 775.0 | 2363. | 13.4 | 5.3 | 308.2 | 45/ 1 |
| 750.0 | 2638. | 11.1 | 5.4 | 308.6 | 43/ 2 |
| 717.0 | 3012. | 7.9 | 5.3 | 309.1 | 44/ 3 |
| 700.0 | 3215. | 6.1 | 6.8 | 309.2 | 53/ 4 |
| 689.0 | 3345. | 4.6 | 6.7 | 309.0 | 60/ 5 |
| 680.0 | 3448. | 6.1 | 3.2 | 311.8 | 67/ 5 |
| 650.0 | 3817. | 4.8 | 2.1 | 314.4 | 92/ 6 |
| 647.0 | 3854. | 4.6 | 1.9 | 314.6 | 96/ 6 |
| 600.0 | 4466. | 2.3 | 1.7 | 318.7 | 163/ 4 |
| 589.0 | 4615. | 1.7 | 1.8 | 319.7 | 184/ 4 |
| 550.0 | 5164. | -1.5 | 1.7 | 322.3 | 232/ 6 |
| 500.0 | 5916. | -6.1 | 1.5 | 325.5 | 266/ 6 |
| 484.0 | 6175. | -7.6 | 1.6 | 326.7 | 276/ 4 |

MONTH 9 DAY 3 HOUR 1800 CST

| P (MB) | Z (M) | T (C) | MIX R | PT (K) | WIND (M/S) |
|---|---|---|---|---|---|
| 970.0 | 392. | 32.8 | 11.4 | 308.6 | 150/ 7 |
| 951.0 | 568. | 28.9 | 10.6 | 306.4 | 154/ 7 |
| 950.0 | 577. | 28.9 | 10.6 | 306.5 | 154/ 7 |
| 900.0 | 1055. | 24.4 | 9.6 | 306.7 | 164/ 7 |
| 850.0 | 1552. | 19.6 | 8.6 | 306.7 | 172/ 4 |
| 800.0 | 2071. | 15.7 | 6.8 | 307.9 | 176/ 2 |
| 771.0 | 2383. | 13.3 | 5.8 | 308.6 | 176/ 2 |
| 750.0 | 2615. | 11.1 | 6.1 | 308.6 | 188/ 3 |
| 729.0 | 2851. | 8.8 | 6.5 | 308.6 | 201/ 4 |
| 700.0 | 3186. | 7.0 | 3.1 | 310.2 | 207/ 6 |
| 665.0 | 3607. | 7.0 | 2.3 | 314.8 | 219/ 6 |
| 650.0 | 3794. | 6.3 | 2.2 | 316.1 | 228/ 4 |
| 600.0 | 4447. | 3.5 | 2.2 | 320.1 | 252/ 5 |
| 582.0 | 4693. | 2.4 | 2.3 | 321.6 | 272/ 3 |
| 550.0 | 5148. | -0.4 | 2.1 | 323.6 | 262/ 2 |
| 500.0 | 5902. | -5.5 | 1.8 | 326.3 | 272/ 5 |
| 472.0 | 6352. | -8.5 | 2.2 | 328.0 | 291/ 6 |
| 463.0 | 6501. | -9.8 | 2.7 | 328.2 | 298/ 7 |
| 450.0 | 6725. | -11.4 | 2.7 | 328.8 | 301/ 7 |
| 400.0 | 7617. | -15.4 | 1.4 | 334.9 | 285/ 8 |